



## A review on Pyrolysis of waste plastics to value added products

S.Karthikeyan<sup>1,\*</sup>, N.Sivakumar<sup>2</sup>, T. K.Manimekalai<sup>3</sup> and C.Sathiskumar<sup>4</sup>

<sup>1,2,4</sup>Department of Chemistry, Chikkanna Govt Arts College, TN, India.

<sup>3</sup>Department of Chemistry, Excel Engineering College, TN, India.

### ARTICLE INFO

#### Article history:

Received: 9 March 2012;

Received in revised form:

25 April 2012;

Accepted: 11 May 2012;

#### Keywords

Pyrolysis,

Plastics,

MSW.

### ABSTRACT

Statistics show that the consumption of plastics has been increasing every year. To reduce environment waste plastic they must be recycled. Among the various types of recycling, pyrolysis in general, offers an environmentally attractive method to decompose wide spectrum of wastes, including waste plastics. Pyrolysis of plastic waste results in char, pyro oil and pyro gases. The derived oils may be used directly as fuel or added to petroleum refinery feed stock. The gases are also useful as fuel and solid char may be used as either smokeless and fuel or activated carbon or can be gasified for production of fuel gases. In this paper a detailed literature of pyrolysis of waste plastic materials is reviewed and the effect of process parameters on the yield of pyrolysis products was discussed.

© 2012 Elixir All rights reserved.

### Introduction

The total world production of plastics presently stands at several million tones, having overtaken the production of steel<sup>1</sup>. According to recent estimates in Europe, plastic wastes represent 15-25% of municipal waste. The amount of plastic materials in Europe was 30 MT during 2000 and it was estimated above to reach 36 MT by 2012<sup>2</sup>. In USA the amount of plastic waste was 24.8 MT in 2000 and 29.7 MT in 2006. The amount of plastic consumed as a percentage of total waste has increased from less than 1% in 1960 to 11.7% in 2006 (Environmental Protection Agency (EPA) report 2000 and 2006). In Japan, 15 MT of plastics are produced annually and 10 MT of plastics are discarded<sup>3</sup>. Similarly in India the amount of plastic waste during 2000/2001 was 2.38 MT and has increased to more than 8 MT by 2010 and is estimated to rise more than 20 MT by 2030<sup>4</sup>. Waste plastics amount to around 20% of the volume and 8% of the weight of all MSW (municipal solid waste) in USA during 2000 which increased to 11.7% by 2006 (Environmental Protection Agency (EPA) 2006 reports)<sup>2</sup>. In China (2000) and Japan (2001) plastics constitute 13% and 7% respectively in MSW<sup>5,6</sup>. Similarly in India, of the total MSW, plastic waste increased from 0.7% in 1971 to 4% in 1995 and 9% in 2003<sup>4,7</sup> and it was estimated to raise more and more in future plastic materials comprise a steadily increasing proportion of the municipal and industrial waste going to landfill. Owing to the huge amount of plastic wastes, recycling of plastics has become a predominant subject in today's plastics industry. Development of technologies for reducing plastic waste, which are acceptable from the environmental standpoint and which are cost-effective, has proven to be a difficult challenge, because of the complexities inherent in the reuse of polymers. Establishing optimal processes for the reuse/recycling of plastic materials thus remains a worldwide challenge in the new century<sup>8</sup>. In recent years several attempts have been made to find new ways and means to recycle plastics like mechanical recycling, biological recycling and thermochemical recycling (incineration and pyrolysis). Thermochemical recycling (pyrolysis) offers an environmentally attractive method to decompose wide variety of

plastic wastes<sup>9</sup>. Several methods for the recycling of waste polymers have been proposed, of which pyrolysis is a promising approach with potential applications. Pyrolysis, i.e., thermal cracking of the polymers to give low molecular weight materials is attractive, but unfortunately gives a very broad range of products<sup>10</sup>. In this paper a detailed literature of pyrolysis of waste plastics materials is reported and the effects of process parameters on the yield of pyrolysis products have been discussed.

### Recycling methods of plastic wastes

Since plastics are non-biodegradable, they cannot be easily returned to the natural carbon cycle; hence the life cycle of plastic materials ends at waste disposal facilities<sup>11</sup>. In most developed societies domestic organic waste, including plastics packaging, is disposed of in sanitary land filled or by incineration. There are several methods for disposal of municipal and industrial plastic waste, i.e. landfill, incineration (energy recovery), true material recycling (similar recycled product or monomer recovery), and chemical recovery<sup>12</sup>. The suitable treatment of plastic wastes is one of the key questions of waste management and is important from energetic, environmental, economical and political aspects<sup>13</sup>. Fig. 1. represents the different routes for plastic waste management being followed.

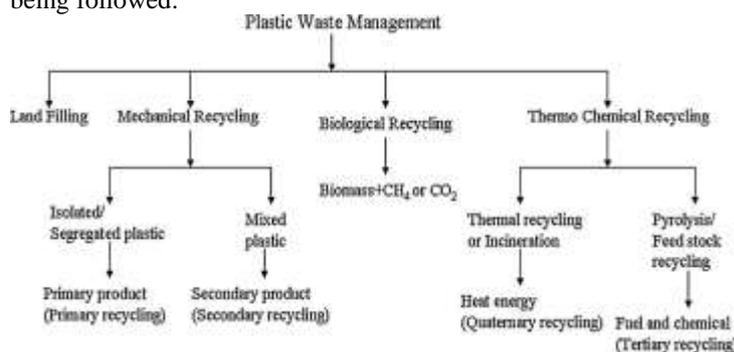


Fig.1. Different routes for plastic waste management

Landfills cause more and more serious problems because of the environment load. Due to the filling of the landfills, cost

consumption is increasing, and therefore significant efforts are being made to increase recycling and re-processing in Europe. Energy produced from plastic waste by burning is very disputable. The mechanical recycling is a process in which the clean and homogenous plastic are granulated and new products are made by e.g. injection molding. The mechanical recycling is economical not only in cases when high purity selectively collected wastes are available<sup>14</sup>. Energy recovery by incineration, a priori, seems to be a suitable solution that takes advantage of the high energy content of plastics but presently is largely questioned, because of the possible emission of toxic compounds (e.g., dioxins, furans). Recycling accounts for a more suitable environmental solution, because it allows for the retrieval of either plastics (mechanical recycling) or fuels/raw chemicals (feedstock recycling) from waste plastics<sup>1</sup>.

Plastic wastes can be classified as industrial and municipal plastic wastes according to their origins; these groups have different qualities and properties and are subjected to different management strategies<sup>15</sup>. Therefore, catalytic pyrolysis is being investigated as a means to address these problems (Lin and Yang, 2007)<sup>16</sup>. Solid waste pyrolysis and gasification offer several benefits over conventional disposal means: they provide a captive energy source and reduce the quantity of waste material to be land filled and the associated cost, the fuel gas and/or liquid may be used in conventional end use systems, and there are minor byproduct and pollutant generating problems<sup>17</sup>.

The thermal pyrolysis of polyolefins takes place through a complex free radical mechanism<sup>18</sup>, giving rise to a wide product distribution that depends on the pyrolysis conditions, namely, heating rate, temperature, and residence time<sup>19-21</sup>. The use of acid catalysts, either in situ in the pyrolysis reactor<sup>22-24</sup> or online in the reforming of pyrolysis volatile products<sup>25,26</sup>, improves the quality of the product stream and decreases the required temperature for pyrolysis. Nevertheless, these strategies involve an increase in the costs of capital and catalyst regeneration, which points to the need to continue exploring the possibilities of catalyst-free pyrolysis.

Generally, the processes are based often on thermal and catalytic cracking or pyrolysis in batch, semi-batch, vessel and tubular reactors. The yields of liquid, gaseous and solid products obtained via pyrolysis/cracking of plastic wastes depend on many parameters such as composition of the wastes mixture, temperature, type of catalyst, residence time in the reactor, type of the reactor and type of the process (multistage or single stage, in gas or liquid phase with a solvent), and heating rate<sup>27</sup>.

#### Effect of temperature, gas flow rate on product yield

Thermal decomposition of natural polystyrene (PS), recycled plastics, low density polyethylene (PE), acrylonitrilebutadienestyrene (ABS), polyenterophthalate of ethylene, and polypropylene (PP) has been carried out. The effects of N<sub>2</sub> flow rate (200-300 cm<sup>3</sup> min<sup>-1</sup>), initial mass fed to the reactor (15-75 mg), temperature (415-490 °C), and heating rate (5-30 K min<sup>-1</sup>) were studied by Encinar and González<sup>19</sup>. The authors observed, plastics produced a hydrocarbon gas and an oil/wax. The solid fraction, in general only is a little part of total weight. The two polyalkene plastics (PE and PP) produced very similar product yields, with high yields of wax and hydrocarbon gas and negligible char yields. The nitrogen flow affects the residence time of vapour phase produced by pyrolysis, and hence a rapid flow serves to remove the products quickly from the reaction zone and hence minimize secondary reactions such as cracking and char formation<sup>28,29</sup>.

The compositions of the pyrolysis products of pure low-density polyethylene (LDPE) and polystyrene (PS) and their mixtures at the temperature range from 300 to 500 °C were reported by Onwudili et al.<sup>30</sup>. Total conversion of LDPE was accomplished at 425 °C and above. Thermal decomposition produced a high yield of liquid oil with a yield of 89.5 wt% and 10.0 wt% gas at a temperature of 425 °C. The oil was a low viscosity dark-brown product with minor waxy components. At higher pyrolysis temperatures, the oil yield decreased due to more cracking and secondary reactions leading to increasing gas yields and the emergence of a char product. Oil yield decreased to 72.4 wt% at a pyrolysis temperature of 450 °C, while gas and char reached 25 wt% and 1.75 wt%, respectively. At 500 °C there was significant formation of char with 15.5 wt % production, while the oil was cracked to large quantities of gas of 47.0 wt% with a corresponding decline in oil yield. It was found that significant increase in gas and char production is a result of secondary reactions of the oil vapours<sup>31</sup>. The production of high yield of hydrocarbon gases and char was observed due to secondary reactions, additional cracking reactions, isomerisation and aromatization. In this work, the author concluded that the optimum oil yield from LDPE was at 425° C with an oil mainly rich in both short-chain and long-chain aliphatic hydrocarbons. The study of the degradation of polystyrene (PS) the reaction temperature was increased to 450 °C and then to 500 °C. At 450 °C, the amount of char was 19.6 wt % of the plastic feed, and this increased further to 30.4 wt% at 500 °C. The increased formation of char led to a decrease in the amount of liquid product. For instance at 425 °C, the oil product was about 97 wt% of the plastic feed, but this reduced to just under 80 wt% at 450 °C, and further increased the 500 °C by more than 12 wt% to about 67 wt%. The increased formation of char led to a decrease in the amount of liquid product. The gaseous product did not show any dramatic increase with temperature, and the maximum amount produced was 2.50 wt% at 500 °C. The authors concluded that the closed batch system can be used to effectively degrade LDPE and polystyrene to produce high grade fuel-like oils for energy production<sup>30</sup>.

Bhaskar et al.<sup>32</sup> have done the pyrolysis of polystyrene (HIPS-Br) containing decabromo diphenylethane (DDE) as a brominated flame retardant with antimony trioxide as a synergist under controlled temperature programmed pyrolysis (two steps) conditions to understand the decomposition behaviour and evolution of brominated hydrocarbons from flame-retardant additives. In the following steps 1. ambient temperature to 330 °C at 5 °C min<sup>-1</sup> and hold for 2 h at 330 °C with an N<sub>2</sub> carrier gas flow of 55 ml/min; 2. 330 - 430 °C at 15 °C min<sup>-1</sup> and hold at 430 °C till the end of the experiment with an N<sub>2</sub> carrier gas flow of 30 ml/min. The yield of liquid products in step 1 from 3P/DDE-Sb (5) is 5 wt% and from 3P/DDE-Sb(0) is 2.4 wt.%. The yield of liquid products in step 2 from 3P/DDE-Sb (5) is 63 wt% and from 3P/DDE-Sb(0) is 78 wt%. Results: The presence of synergist with the DDE flame retardant has significant effect on the liquid, gas and residue, which is different than the DDO flame retardant mixed plastics. The yield of liquid products from 3P/ DDE-Sb (5) is 15 wt% less than 3P/DDE-Sb(0). The yield of gaseous and residue products are higher from 3P/DDE-Sb (5) than 3P/DDE-Sb(0) pyrolysis. In both the cases, the density of the step 1 liquid products is lower than the step 2 liquid products due to the low molecular weight hydrocarbons which are formed during low temperature pyrolysis (330 °C for 2 h).

The plastic mixture used for the experiments was composed of 40 wt% high density polyethylene (HDPE), 35 wt% polypropylene (PP), 18 wt% polystyrene (PS), 4 wt% poly(ethylene terephthalate) (PET) and 3% poly(vinyl chloride) PVC the pyrolysis experiment was carried out by Lopez et al.<sup>33</sup>. The temperature 440 °C and Nitrogen was passed during the whole experiment at a rate of 1 dm<sup>3</sup> min<sup>-1</sup> to sweep the decomposition products from the reaction medium. The pyrolysis yields obtaining the thermal process liquid 80 wt %, gas 17 wt% and char 3 wt% .

The fractions of waste polypropylene and polyethylene were pyrolyzed in a pyrolysis plant under different conditions viz., the reaction temperature (650-750 °C), the feed rate, and the kind of fluidizing medium on the product spectrum were investigated by Jung et al.<sup>34</sup>. An increase in the reaction temperature led to a decrease in oil production and an increase in gas production due to the fact that the heavier components were converted into gas components through secondary cracking reactions at elevated temperatures. The amount of gas production summed up to 65.9 wt% at 746 °C for the Polypropylene fraction and to 59.3 wt% at 728 °C for the Polyethylene fraction. The higher amount of gas production for the PP fraction implies the easier degradation of polypropylene (PP) compared to polyethylene (PE), due to the intramolecular radical transfer. The amount of oil production decreased from 43.1 to 29.6 wt % along with the temperature in the case of the PP fraction, and from 61 to 38.2 wt % in the case of the PE fraction. The content of BTX aromatics in the oil was 53 wt % at 746 °C for the PP fraction, and 32 wt% at 728 °C for the PE fraction. For both feed materials, it was found that the concentration of BTX aromatics in the oil increased along with the reaction temperature.

The thermal degradation of real municipal waste plastic (MWP) obtained from Sapporo, Japan and model mixed plastics (PE/PP/PS/PVC/PET) was carried out at atmospheric pressure at 430 °C was investigated by Bhasker et al.<sup>35</sup>. At this temperature plastics (3P/PVC, 3P/PVC PE and MWP) undergo pyrolysis, the product yield were liquid 70 wt %, gas 25 wt% and residue 5 wt%, liquid 53 wt %, gas 34 wt% and residue 13 wt %, liquid 59 wt %, gas 25 wt% and residue 16 wt% The liquid products (59 wt%) produced with the MWP (20 g) were higher than 3P/PVC/PET and lower than 3P/PVC liquid products. Here the investigators were compelled to conclude that the presence of PET has predominant effect on the formation of liquid products. The additional chlorinated hydrocarbons observed in MWP liquid products than 3P/PVC liquid products were due to the presence of PET in MWP, and chlorine containing esters of benzoic acid were observed as additional chlorinated hydrocarbons. The influences of some process condition on char, liquid and gas yield presented by different authors is shown in Table.1.

#### Effect of catalyst on the product yield

Addition of the catalyst enhances the conversion and fuel quality. As compared to the purely thermal pyrolysis, the addition of catalyst in polyolefin pyrolysis, significantly lowers the pyrolysis temperature and time, and a significant reduction in the degradation temperature and reduction time<sup>36</sup>. Under a catalytic conditions result in an increase in the conversion rate for a wide range of polymers at much lower temperatures than the thermal pyrolysis<sup>37-39</sup>. Oils obtained by catalytic pyrolysis contain less olefins and more branched hydrocarbon and aromatic content<sup>40</sup>.

The studies reported in the literature that the preferred plastics for chemical recycling are polyethylene, polypropylene and polystyrene. The temperature range of pyrolysis is wide (350–900 °C) and catalysts can be used in most cases to modify the structure of products and decrease the energy consumption. Generally used catalysts for pyrolysis of plastic wastes are mordenite, FCC, USY, ZSM-5, etc., but the ZSM-5 and FCC catalysts provided the best possibility to yield hydrocarbons in the boiling range of gasoline were investigated by Miskolczi et al.<sup>14</sup>. The pyrolysis of real waste plastics (high-density polyethylene and polypropylene) has been investigated in a pilot scale horizontal tube reactor at 520 °C temperature in the presence of ZSM-5 catalyst. The decomposition reactions resulted in different hydrocarbons, when waste agricultural polyethylene degrades the yields of gases of 12.2%, gasoline of 34.5% and light oil of 24.1% in the presence of ZSM-5 catalyst. In consequence of catalyst application, gasoline yield increased with 94.4% and 64.5% in the case of agricultural waste and packaging waste, while those of light oil were 41.3% and 28.5%. The volatile yield increasing efficiency of ZSM-5 is higher in gasoline, than in light oil. Furthermore catalyst increased the gas volume in the highest 139.8% and 195.7% in the case of polyethylene and polypropylene. Those phenomena could be explained with the microporous and macroporous surface areas of ZSM-5 catalyst. The microporous surface of ZSM-5 is 235.5m<sup>2</sup>/g while the BET surface area is 319.4 m<sup>2</sup>/g. Presumably, the primary cracking reactions of waste polymer may proceed on the macroporous surface of catalyst, while the smaller fragments are cracked on its microporous surface, because it was earlier found that the difference in catalyst pore structure could result in considerable variance of product yields<sup>41, 42</sup>.

A mixture of post-consumer polyethylene/polypropylene/polystyrene (PE/PP/PS) with polyvinyl chloride (PVC) waste was pyrolyzed over cracking catalysts using a fluidizing reaction system operating isothermally at ambient pressure. The influences of catalyst types and reaction conditions including reaction temperatures, ratios of catalyst to plastic feed, flow rates of fluidizing gas and catalyst particle sizes were examined by Lin et al.<sup>43</sup>. The different catalysts used including zeolite-based such as ZSM-5, BEA, USY, MOR, and modified nanocrystalline of Y, and ZSM-5<sup>44-50</sup>, amorphous silica-aluminas (SAHA) and the family of mesoporous MCM materials<sup>51-55</sup>. Both the carbon number distribution of the products of hospital post-consumer PE/PP/PS/PVC waste plastics cracking at 390 °C over various catalysts and the nature of the product distribution were found to vary with the catalyst used. The yield of volatile hydrocarbons for zeolitic catalysts (ZSM- 5NHUSY) gave higher yield than non-zeolitic catalysts (SAHA) and zeolite-based equilibrium FCC catalyst (FCC-R1), and the highest was obtained for ZSM-5 (88.3 wt %). Overall, the bulk of the products observed with these acidic cracking catalysts (FCC-R1, HUSY, ZSM-5 and SAHA) was in the gas phase with less than 4wt% liquid collected. FCC process with the fluidized-bed reactor system has been shown to have a number of advantages in the catalytic pyrolysis of commingled plastic waste; it is characterized by excellent heat and mass transfer, much less prone to clogging with molten polymer and gives a nearly constant temperature throughout the reactor. Spent FCC equilibrium catalyst can be better option since it may lead to a cheaper process with

valuable products and can be further used as an adequate approach for the catalytic recycling of plastic waste<sup>43</sup>.

Two series of the experiments of waste polymers (polyethylene (PE), polystyrene (PS) and polypropylene (PP) and their mixtures were used as a raw materials) by using a catalyst alkaline and base metal oxides (MgO and CaO) was carried out by Walendziewski<sup>56</sup>. The first series of the polymer cracking experiments was carried out in a glass reactor of 0.5 dm<sup>3</sup> volume at atmospheric pressure and in a temperature range 350-420 °C, the second one in autoclaves under hydrogen pressure (~3-5 MPa) in the temperature range 380-440 °C. Thermal and catalytic cracking can be carried out with 70-98 wt% efficiency in the temperature range 350-440 °C. Process in the batch cycle in the presence of alkaline catalyst proceeds with similar temperature range 390-410 °C. An increase in the amount of the applied cracking catalyst (from 0 to 10 wt %) in the cracking of the mixture of polystyrene (PS) and polyethylene (PE) resulted in lowering of the average cracking temperature. In the catalytic process the conversion of polystyrene (PS) was the lowest one while the highest conversions were obtained for mixed (PE+PS) feed, although the difference in plastic conversion were not large. Products of polymer cracking are highly unsaturated containing olefins and diolefins. Application of cracking catalyst result in lowering of polymers cracking process temperature as well as boiling temperature range and density of the obtained liquid products.

It was reported in the work done by Achilias et al<sup>25</sup>, that the recycling of either model polymers or waste products based on low-density polyethylene (LDPE), high-density polyethylene (HDPE) or polypropylene (PP) was examined using FCC catalyst by pyrolysis method. The reactor was filled with 0.7 g of the FCC catalyst and the piston was filled with the polymer (1.5 g). The system was always heated in the presence of N<sub>2</sub> (30 mL/min) and the reaction temperature 450 °C. The author concluded that the pyrolysis temperature is rather low. A small gaseous fraction was obtained from all polymers and the relative amounts of gas and liquid fraction are very much dependent on the type of polymer used as raw material. The oil and gaseous fractions recovered presented mainly aliphatic composition consisting of a series of alkanes and alkenes of different carbon number with a great potential to be recycled back into the petrochemical industry as a feedstock for the production of new plastics or refined fuels.

Plastic wastes coming from a waste packaging separation and classification plant have been pyrolysed in a semibatch nonstirred autoclave swept by a continuous flow of N<sub>2</sub> such as that described by de Marco et al<sup>57</sup>. The plastic waste contains 39.5% PE, 34.2% PP, 16.2% PS and EPS, and some other minor materials. Temperatures in the range 400-600 °C have been explored, and the authors found that over 460 °C total thermal decomposition of the waste plastics takes place. Three catalysts have been tested: HZSM-5, red mud and AlCl<sub>3</sub>. Solid yields about 5-7%, liquid yields in the range 40-70% and gas yields in the range 12-24% were obtained. The increasing pyrolysis temperature resulted in is a decrease in liquid yield and an increase in gas yield. Both the increase in gas yield and the decrease in the viscosity of the liquids are obviously due to the higher thermal cracking that is produced at higher temperatures. HZSM-5 is a convenient catalyst since it produces more valuable liquids (more aromatic and of lower molecular weight). AlCl<sub>3</sub> also generates lighter liquid products. Red mud produces more liquids which in addition are less waxy and more aromatic

than those of thermal pyrolysis, but no effect of red mud on the oils carbon number was observed.

The catalytic degradation of waste plastics (polyethylene and polystyrene) in a temperature range of 410-450 °C was investigated by Miskolczi et al<sup>58</sup> in a batch reactor over different catalysts (FCC, ZSM-5 and clinoptilolite). The effects of catalysts and their average grain size on the properties of main degradation products (gases, gasoline and diesel oil) were discussed. Both equilibrium FCC catalyst and natural clinoptilolite zeolite catalyst had good catalytic activity to produce light hydrocarbon liquids, and ZSM-5 catalyst produced the highest amount of gaseous products. The gas and liquid yields increased with increasing temperature of degradation, and nearly complete cracking could be attained at 450 °C. The cracking temperature and catalyst grain size significantly affected the yields, but gas yields depended mainly on the type of catalyst.

A commercial FCC catalyst based on a zeolite active phase has been used in the catalytic pyrolysis of HDPE and the experimental runs have been carried out in a conical spouted bed reactor at 500 °C with the freehand mildly steamed catalysts as described by Olazar et al<sup>59</sup>. The bed was initially made up of 30 g of catalyst (particle size between 20 and 90 mm), and the continuous polymer feed rate was 0.5 g/min for 6-7 h, which means that 180-210 g of polymer have been fed into the catalyst bed. The nitrogen flow rate has been set at 1.2 times the minimum spouting velocity, 0.7 L/min (measured at normal conditions).

Mertinkat et al<sup>60</sup> studied the effect of temperature on product distribution in the catalytic pyrolysis of polyethylene over fresh FCC catalyst in a fluidized bed reactor. For a reaction temperature of 450 °C, these authors reported 48.3 wt% gases, 37.6 wt% liquids and 14.1 wt% soot or coke. The results obtained at 515 °C are also very similar 51.8 wt% gases, 39 wt% liquids and 9.2 wt% soot or coke.

Lin and Yang<sup>61</sup> studied the catalytic pyrolysis of polypropylene over FCC spent catalyst in a fluidized bed reactor. Operating at 450 °C they obtained 34.2 wt% gases and 56 wt% liquids and 9.1 wt% coke and residue. These results are intermediate between those obtained in this study with the fresh and mildly steamed catalyst. Thus, it can be informed that the more severe the steaming the lower the gas and light oil fraction and higher the diesel-oil fraction.

The influence of ZSM-5 zeolite and Red Mud in the pyrolysis of plastic wastes (PE 40 Wt% + PP 35 Wt% + PS 18 Wt% + PET 4 Wt% + PVC 3Wt %) had been studied by Lopez et al<sup>62</sup>. Both catalysts have been tested in pyrolysis of a mixture of plastics which resembles municipal plastic wastes, at 440 and 500 °C in a 3.5dm<sup>3</sup> semibatch reactor. Both catalysts were thoroughly mixed with the plastic sample in a proportion of 10 wt% in all the experiments (10 g of catalyst/100 g of plastics). When the pyrolysis temperature was raised from 425 to 500 °C, the liquid yield decreases and consequently the gas production increases. This behavior has also been reported by many other authors<sup>63-66</sup> and it is attributed to the stronger cracking of C-C bonds that takes place at higher temperatures, which gives rise to lighter hydrocarbons with shorter carbon chains. Among the temperatures at which total conversion was achieved, 440 °C was the lowest one and at the same time the one that yields the greatest amount of liquids, while 500°C is leads to the highest gas yield. The influence of Red Mud in pyrolysis yields is lesser than that of the zeolite; slightly higher gas yields than without

catalysts are obtained at both 440 and 500 °C (4 and 7wt% higher respectively), which indicates that its cracking ability is lower than that of the zeolite, as was expected according to its lower surface area and acidity .

#### The mixture of polymer waste (LDPE/HDPE/PP) was pyrolyzed over various catalysts

(ZSM-5, MOR, USY, MCM-41 and ASA) using a laboratory fluidized-bed reactor operating isothermally at ambient pressure was investigated by Ta-Tung et al.<sup>66</sup>. The yield of volatile hydrocarbons for zeolitic catalysts (ZSM-5 >MOR> USY) gave higher yield than non-zeolitic catalysts (MCM-41 > ASA). MCM-41 with large mesopores and ASA with weaker acid sites resulted in a highly olefinic product and gave a wide carbon number distribution, whereas USY yielded a saturate-rich product with a wide carbon number distribution and substantial coke levels. The influence of operation at conditions including temperature (290-420 °C), flow rates of fluidizing gas (270-900 mLmin<sup>-1</sup>), and ratios of LDPE/HDPE/PP polymer waste to catalyst feed ratio (0.1:1 to 1:1). Some similar trends in product yields were observed with USY as the reaction temperature was increased. Gaseous yields increased and involatile residues (unreacted or partially reacted LDPE/HDPE/PP polymer waste) and liquids decreased. Under appropriate reaction conditions and suitable catalysts it can have the ability to control both the product yield and product distribution from polymer degradation, potentially leading to a cheaper process with more valuable products.

Waste high-density polyethylene (HDPE) was degraded catalytically using BaCO<sub>3</sub> as a catalyst under different conditions of temperature, catalyst polymer ratio and time were studied by Rasul Jan et al.<sup>67</sup>. The basic catalyst (BaCO<sub>3</sub>) has been used for the catalytic cracking of HDPE. The catalytic reaction was carried out at 450 °C. Where MgCO<sub>3</sub> has been used as a catalyst, it could be observed that keeping the same reaction conditions, the % oil yield (33.60%) is higher with MgCO<sub>3</sub> as compared to the % oil yield (29.60%) obtained with BaCO<sub>3</sub> catalyst. Similarly when CaCO<sub>3</sub> was used as a catalyst under the same reaction conditions, the obtained % oil yield was 32.20%. The decreasing trend in oil yield can be established as MgCO<sub>3</sub> (33.60%)>CaCO<sub>3</sub> (32.20%)> BaCO<sub>3</sub> (29.60%). It was due to the fact that as we move down along the alkaline earth metals group in the periodic table, hardness of the basic catalyst decreases. In other words MgCO<sub>3</sub> is a harder base than BaCO<sub>3</sub> catalyst<sup>68</sup>. Thus the hard base had strong affinity towards a hard acid which is H<sup>+</sup> in this case. Thus the H<sup>+</sup> from the surface of polymer had been easily abstracted by MgCO<sub>3</sub> as compared to BaCO<sub>3</sub> and the conversion in the former case had consequently higher. For a period of 1 h using 0.5 g, 1.0 g, 1.5 g and 2.0 g of the catalyst for a fixed weight of the sample (5 g). The amount of the catalyst increases, a slight and gradual decrease in the total percent conversion, oil yield and wax product occurs. Mastral et al.<sup>69</sup> and Schirmer et al.<sup>70</sup> were demonstrated the optimum amount of catalyst (smaller in this case) is required to produce maximum quantity of the product (oil product) that is the product of interest on the basis of fuel point of view. Thus enhanced oil product increases output of the degradation reaction and cost of the process is reduced comparatively. The use of BaCO<sub>3</sub> as a catalyst for the conversion of HDPE into fuel oil greatly reduce the formation of wax<sup>67</sup>.

It was observed in the work carried out by Jasmin shah et al.<sup>71</sup> with low density polyethylenes (LDPE) were catalytically pyrolysed in a home assembled batch reactor under atmospheric

pressure. It can be seen from these results that maximum conversion was obtained at 400 °C. The effect of catalyst weight on the catalytic pyrolysis of polyethylene for these catalysts was investigated in the range of 0-2.5 g for 5 g of LDPE sample at optimum temperature. It was observed that 1 g of catalyst weight was found as optimum weight for 5 g of LDPE sample in case of SiO<sub>2</sub> and CaC<sub>2</sub>, 1.5 g for MgO and Al<sub>2</sub>O<sub>3</sub> and 2 g for ZnO and equimolar mixture of SiO<sub>2</sub> and Al<sub>2</sub>O<sub>3</sub> as catalyst. This was due to the fact that at higher catalyst weight the rate of reaction increases the cracking process, which results in maximum gaseous product. Though CaC<sub>2</sub> was better on the basis of reaction time, however the efficiency of conversion into liquid for SiO<sub>2</sub> was found to be maximum in case of LDPE at optimum conditions. The authors concluded that the two catalysts had been picked up as suitable catalysts for catalytic pyrolysis of polyethylene.

Three different BET surface area of ZSM-5 zeolite (fresh, spent and regenerated) catalyst in the pyrolysis of plastic mixture was carried out by Lopez et al.<sup>33</sup>. 10 g of zeolite were mixed with the 100 g plastic sample at the beginning of the experiment (liquid phase contact). Nitrogen was passed through during the whole experiment at a rate of 1 dm<sup>3</sup> min<sup>-1</sup> to sweep the decomposition products from the reaction medium, the reaction temperature 440 °C. The data revealed that among the above three catalysts, spent ZSM-5 zeolite is the one of the best that gave the highest percentage of oil at 440 °C. The sequence of the catalyst, that shifts the reaction towards the oil is spent ZSM-5> regenerated ZSM-5> fresh ZSM-5.

The effects of Pt/Al<sub>2</sub>O<sub>3</sub> and Rh/Al<sub>2</sub>O<sub>3</sub> catalysts on the pyrolysis of low-density polyethylene at a temperature of 425 °C and residence time of 1 h was investigated by Nagi Insura et al.<sup>72</sup>. 1 gm of Pt/Al<sub>2</sub>O<sub>3</sub> pellets were mixed with 10 gm of LDPE sample and loaded into autoclave reactor at 425 °C. The product yield was oil 88.1 wt%, gas 9.80 wt% and char 2.10 wt%. 1 gm of Rh/Al<sub>2</sub>O<sub>3</sub> pellets were mixed with 10 gm of LDPE sample and loaded into autoclave reactor at 425 °C. The product yield was oil 85.1 wt %, gas 11 wt % and char 3.52 wt%. The above two catalyst the oil yield of Pt/Al<sub>2</sub>O<sub>3</sub> catalyst was more than Rh/Al<sub>2</sub>O<sub>3</sub> catalyst.

#### Conclusion

Presently pyrolytic oil is mainly used directly as a fuel or added petroleum refinery stock and important source of refined chemicals. To tap full potential of pyrolysis oil, need emerges for its commercialization by making it transportable. The nitrogen flow affects the residence time of the vapour phase produced by pyrolysis, and hence a rapid flow serves to remove the products quickly from the reaction zone and hence minimize secondary reactions such as cracking and char formation.

The plastic pyrolysis can be carried out by acid, base and non catalyst. It could be observed that the oil yield of non catalytic plastic pyrolysis was higher than acid catalytic pyrolysis. The oil yield of basic catalytic pyrolysis was lower than the acid catalytic pyrolysis. The decreasing trend in oil yield can be established as non catalyst > acid catalyst > basic catalyst. The presence of suitable catalyst decreases the cracking temperature and increases the plastic conversion, in comparison with thermal process. As the catalyst ratio increases, a slight and gradual decrease in the total percent conversion, oil yield and wax products occur.

The yields of both gas and liquid products are affected by the grain size of catalysts. Smaller the catalyst grain size resulted in significantly higher yields of volatile fractions (gases,

liquids), because of greater surface of catalyst grains. For plastic pyrolysis, the increase in gas yield and the decrease in the viscosity of the liquids are obviously due to the higher thermal cracking that is produced at higher temperatures. Liquid properties are considerably changed in the presence of catalysts. Naptha-likeliquids obtained by thermo-catalytic cracking of polymer wastes had more favourable properties for further application, then those obtained by thermal cracking e.g. higher octane numbers.

#### References

1. J. Aguado, D.P. Serrano and J.M. Escola, *Ind. Eng. Chem. Res.*, 47, 7982–7992 (2008).
2. N. Miskolczia, L. Bartha, G. Deak and B. Jover, *Polym.Degrad. Stab.*, 86, 357–66 (2004).
3. Y.Uemura, K. Baba, H. Ohe, Y. Ohzuno and Y. Hatate, *The Journal of Material Cycles and Waste Manage.*, 5, 94–7 (2003).
4. N.H. Muthaa, M. Patel and V. Premnath, *Resources. Conservation and Recycling.*, 47, 222–44 (2006).
5. Waste Management in China: Issues and recommendations; May 2005  
<http://siteresources.worldbank.org/INTEAPREGTOPURBDEV/Resources/China-Waste-Management1.pdf>
6. Toward an Era of Environmental Revolution, Japan[<http://www.env.go.jp/en/wpaper/2004/02.pdf>].
7. S. Gupta, K. Mohan, R. Prasad, S. Gupta and A. Kansal, *Resources Conservation and Recycling.*, 24, 137–54 (1998).
8. Sachin Kumar, A.K. Panda and R.K. Singh, *Resources, Conservation and Recycling.*, 55, 893–910 (2011).
9. A.K. Panda, R.K. Singh and D.K. Mishra, *A world prospective Renewable and Sustainable Energy Reviews.*, 14, 233–248 (2010).
10. T.T Weia, K.J. Wua, S.L. Leeb and Y.H Lina, *Resources, Conservation and Recycling.*, 54, 952–961 (2010).
11. G. Luo, T. Suto, S. Yasu and K. Kato, *Polym. Degrad. Stab.*, 70, 97–102 (2007).
12. N. Miskolczi, L. Bartha and A. Angyal, *Macromolecules Symposium.*, 245–246:599–606.
13. C. Delattre, M. Forissiera and I. Pitault, *Chem. Eng. Sci.*, 56(4), 1337–45 (2001).
14. N. Miskolczi, A. Angyal, L. Bartha and I. Valkai, *Fuel Process. Technol.*, 90, 1032–1040 (2009).
15. A.G. Buekens and H. Huang, *Resources Conservation and Recycling.*, 23, 163–81 (1998).
16. Y.H. Lin, M.H. Yang, *Appl Catal B: Environ.*, 69, 145–53 (2007a).
17. A.G. Buekens and J.G. Schoeters, *Conserv. Recycl.*, 9, 253 (1986).
18. T. Ueno, E. Nakashima and K. Takeda, *Polym. Degrad. Stab.*, 95, 1862–1869 (2010).
19. J.M. Encinar and J.F. Gonzálezb, *Fuel Process. Technol.*, 89, 678–686 (2008).
20. A.M. Al-Salem and P. Lettieri, *Chem. Eng. Res. Des.*, 88, 1599–1606 (2010).
21. U. Hujuri, A.K. Ghoshal and S. Gumma, *Waste Manage.*, 30, 814–820 (2010).
22. A. Marcilla, M. Beltrán, F. Hernández and R. Navarro, *Appl. Catal. A: Gen.*, 278, 37–43 (2004).
23. A. Marcilla, M. Beltrán and R. Navarro, *Appl. Catal. B: Environ.*, 86, 78–86 (2009).
24. D.P. Serrano, J. Aguado, J.M. Escola, E. Garagorri, J.M. Rodríguez, L. Morselli, G. Palazzi, and R. Orsi, *Appl. Catal. B: Environ.*, 49, 257–265 (2004).
25. D.S. Achilias, C. Roupakias, P. Megalokonomos, A.A. Lappas and E.V. Antonakou, *J. Hazard. Mater.*, 149, 536–542 (2007).
26. S. Chaianansutcharit, R. Katsutath, A. Chaisuwan, T. Bhaskar, A. Nigo, A. Muto and Y. Sakata, *J. Anal. Appl. Pyrol.*, 80, 360–368 (2007).
27. M. Stelmachowski, *Energy Conversion and Management.*, 51, 2016–2024 (2010).
28. W. J. Hall and P. T. Williams, *Energy & Fuels.*, 20, 1536–1549 (2006).
29. M.J. Antal Jr, G. Varhegyi, *Ind. Eng. Chem. Res.*, 34, 703–717 (1995).
30. J.A. Onwudili, Nagi Insura, P.T. Williams, *J. Anal. Appl. Pyrol.*, 86, 293–303 (2009).
31. R.W.J. Westerhout, J. Waanders, J.A.M. Kuipers and W.P.M. Van Swaaij, *Ind. Eng. Chem. Res.*, 37, 2293–2300 (1998).
32. T. Bhaskar, W.J. Hall, N.M.M. Mitran, A. Muto, P.T. Williams and Y. Sakata, *Poly. Degrad. Stab.*, 92, 211–221 (2007).
33. A. López, I. de Marco, B.M. Caballero, A. Adrados and M.F. Laresgoiti, *Waste Manage.*, 31, 1852–1858 (2011).
34. S.Jung, M. Cho, B. Kang and J. Kim, *Fuel Process. Technol.*, 91, 277–28 (2010).
35. T. Bhaskar, Md.A. Uddin, K. Murai, J. Kaneko, K. Hamano, T. Kusaba, A. Muto and Y. Sakata, *J. Anal. Appl. Pyrol.*, 70, 579–587 (2003).
36. H. Ohkita, R. Nishiyama, Y. Tochihara, T. Mizushima, N. Kakuta and Y. Morioka, *Industrial & Engineering Chemistry Research.*, 32(12), 3112–6 (1993).
37. W.B. Ding, J. Liang and L.L. Anderson, *Fuel Process. Technol.*, 51(1–2), 47–62 (1997).
38. D.W. Park, E.Y. Hwang, J.R. Kim, J.K. Choi, Y.A. Kim and H.C. Woo, *Polym. Degrad. Stab.*, 65(2), 193–8 (1999).
39. S.Y. Lee, *Polym. Degrad. Stab.*, 74(2) 297–305 (2001).
40. Y.H. Seo, K.H. Lee and D.H. Shin, *J. Anal. Appl. Pyrol.*, 70(2), 383–98 (2003).
41. F. Pinto, P. Costa, I. Gulyurtulu and I. Cabrita, *J. Anal. Appl. Pyrol.*, 51, 57–71 (1999).
42. P.N. Sharrath, Y.-H. Lin, A.A. Garforth and J. Dwyer, *Industrial & Engineering Chemistry Research*, 36, 5118–5124 (1997).
43. H.T. Lin, M.S.Huang, J.W. Luo, L.H. Lin, C.M. Lee and K.L. Oub, *Fuel Process. Technol.*, 91, 1355–1363 (2010).
44. H. Ohkita, R. Nishiyama, Y. Tochihara, T. Mizushima, N. Kakuta, Y. Morioka, Y.Namiki, H. Katoh, H. Sunazyka, R. Nakayama and T. Kuroyanagi, *Ind. Eng. Chem. Res.*, 32, 3112–3116 (1993).
45. Y. Uemichi, J. Nakamura, T. Itoh, A. Garforth and J. Dwyer, *Ind. Eng. Chem. Res.*, 38, 385–390 (1999).
46. J. Aguado, D.P. Serrano, J.M. Escola, E. Garagorri and J.A. Fernandez, *Polym. Degrad. Stab.*, 69, 11–16 (2000).
47. A. Dawood and Miura, *Polym. Degrad. Stab.*, 76, 479–487 (2002).
48. K. Gobin and G. Monos, *Polym. Degrad. Stab.*, 86, 225–231 (2004).
49. Z. Gao, K. Ksuyoshi, I. Amasaki and M. Nakada, *Polym. Degrad. Stab.*, 80, 269–274 (2003).
50. A. Marcilla, A. Gomez-Siurana and F. Valdes, *Polym.Degrad. Stab.*, 92, 197–204 (2007).

51. A. Ghanbari-Siakhalu Philipou, A.A. Garfort, C.S. Cundy and J. Dwyer, *J. Mater. Chem.*, 11,569–577 (2001).
52. Y.H. Lin and M.H. Yang, *Anal. Appl. Pyrol.*, 83, 101–109 (2008).
53. Y.H. Lin, M.H. Yang, T.F. Yeh and M.D. Ger, *Polym. Degrad. Stab.*, 86, 121–128 (2004).
54. S. Ali, A.A. Garforth, D.H. Harris and Y. Uemichi, *Catal. Today.*, 75, 247–255 (2002).
55. Y.H. Lin and M.H. Yang, *Appl. Catal. A: Gen.*, 328, 132–139 (2007).
56. J. Walendziewski, *Fuel*, 81, 473–481 (2002).
57. I. de Marco, B.M. Caballero, A. López, M.F. Laresgoiti, A. Torres and M.J. Chomón, *J. Anal. Appl. Pyrol.*, 85, 384–391 (2009).
58. N. Miskolczi, L. Bartha, Gy. Deák, *Polym. Degrad. Stab.*, 91, 517–526 (2006).
59. M. Olazar, G. López, M. Amutio, G. Elordi, R. Aguado and J. Bilbao, *J. Anal. Appl. Pyrol.*, 85, 359–365 (2009).
60. J. Mertinkat, A. Kirsten, M. Predel and W. Kaminsky, *J. Anal. Appl. Pyrol.*, 49, 87 (1999).
61. Y.H. Lin and M.H. Yang, *Appl. Catal. B: Environ.*, 69, 145 (2007).
62. A. López, I. de Marco, B.M. Caballero, M.F. Laresgoiti, A. Adrados and A. Aranzabal, *Appl. Catal. B: Environ.*, 104, 211–219 (2011).
63. J. Aguado and D.P. Serrano, *The Royal Society of Chemistry*, Cambridge, UK, 1999.
64. M.R. Hernández, A. Gómez, A.N. García, J. Agulló and A. Marcilla, *Appl. Catal.*, A 317, 183–194 (2007).
65. A.M. Li, X.D. Li, S.Q. Li, Y. Ren, Y. Chi, J.H. Yan and K.F. Cen, *J. Anal. Appl. Pyrol.*, 50, 149–162 (1999).
66. T.T. Wei, K.J. Wua, S.L. Leeb, Y.H. Lina, *Resources, Conservation and Recycling.*, 54, 952–961 (2010).
67. M. Rasul Jan, J. Shah and H. Gulab, *Fuel Process. Technol.*, 91, 1428–1437 (2010).
68. J.E. Huheey, *Inorganic Chemistry: Principles of Structure and Reactivity*, New York, 1972.
69. J.F. Mastral, C. Berrueco, M. Gea and J. Ceamanos, *Polym. Degrad. Stab.*, 91, 3330–3338 (2006).
70. J. Schirmer, J.S. Kim and E. Klemm, *J. Anal. Appl. Pyroly.*, 60, 205–217 (2001).
71. J. Shah, M. R. Jan, F. Mabood and F. Jabeen, *Energy Conversion and Management.*, 51, 2791–2801 (2010).
72. N. Insura, J.A. Onwudili, and P.T. Williams, *Energy & Fuels.*, 24, 4231–4240 (2010).

**Table.1. The influences of some process condition on char, liquid and gas yield presented by different authors**

Precursor	Catalyst	Precursor / Catalyst ratio	Temperature °C	N <sub>2</sub> Gas flow rate mL / min	Yield %			Reference
					Char	Gas	Oil	
PS	non catalyst	-	415-490	200-300	1.95	2.28	95.77	Encinar et al. <sup>19</sup>
LDPE	non catalyst	-	415-490	200-300	0.18	18.17	81.65	Encinar et al. <sup>19</sup>
ABS	non catalyst	-	415-490	200-300	1.12	2.89	95.99	Encinar et al. <sup>19</sup>
PET	non catalyst	-	415-490	200-300	9.37	51.6	39.02	Encinar et al. <sup>19</sup>
PP	non catalyst	-	415-490	200-300	0.11	16.55	83.34	Encinar et al. <sup>19</sup>
LDPE	non catalyst	-	425	n.d.	0.5	10	89.5	Onwutuli et al. <sup>30</sup>
LDPE	non catalyst	-	450	n.d.	1.75	25	72.4	Onwutuli et al. <sup>30</sup>
LDPE	non catalyst	-	500	n.d.	15.5	47	36.5	Onwutuli et al. <sup>30</sup>
PE+PP+PS+PVC	non catalyst	-	430	10	5	25	70	Bhasker et al. <sup>35</sup>
PE+PP+PS+PVC+PET	non catalyst	-	430	10	13	34	53	Bhasker et al. <sup>35</sup>
MWP	non catalyst	-	430	10	16	25	59	Bhasker et al. <sup>35</sup>
PE+PS+PP+PVC+PET+ABS	non catalyst	-	460	n.d.	6	53	41	Macro et al. <sup>57</sup>
PE+PS	non catalyst	-	350-440	n.d.	6.3	3.3	87.8	Walendziewski <sup>56</sup>
PE+PP	non catalyst	-	350-440	n.d.	5.1	2.7	88.3	Walendziewski <sup>56</sup>
HDPE+PS(crushed)	non catalyst	-	410-450	n.d.	49	3	48	Miskolczi et al. <sup>58</sup>
HDPE+PS(uncrushed)	non catalyst	-	410-450	n.d.	42	3	55	Miskolczi et al. <sup>58</sup>
PP	HSCLZ4	n.d.	400	n.d.	0-9	53-75	15-46	Stelmachowski et al. <sup>27</sup>
PE + PP	Ga-ZSM5	n.d.	270-550	n.d.	2-18	34-44	36-60	Stelmachowski et al. <sup>27</sup>
LDPE	FCC	1:2	450	30	19.4	8.5	72.1	Achilias et al. <sup>25</sup>
HDPE	FCC	1:2	450	30	52.5	3.3	44.2	Achilias et al. <sup>25</sup>
PP	FCC	1:2	450	30	20	15.3	64.7	Achilias et al. <sup>25</sup>
HDPE+PS	FCC(Uncrushed)	1:10	410-450	n.d.	27	5	68	Miskolczi et al. <sup>58</sup>
HDPE+PS	ZSM-5(Uncrushed)	1:100	410-450	n.d.	30	12	58	Miskolczi et al. <sup>58</sup>
HDPE+PS	FCC(Crushed)	0.1:10	410-450	n.d.	13	7	80	Miskolczi et al. <sup>58</sup>
HDPE+PS	ZSM-5(Crushed)	0.1:10	410-450	n.d.	7	20	73	Miskolczi et al. <sup>58</sup>
HDPE+PS	CiIn(crushed)	0.1:10	450	n.d.	20	6	74	Miskolczi et al. <sup>58</sup>
HDPE+PS	CiIn(uncrushed)	0.1:10	450	n.d.	35	4	61	Miskolczi et al. <sup>58</sup>
LDPE+HDPE+PP	MCM-41	4:6	270	570	8.1	86.7	5.2	Wei et al. <sup>10</sup>
LDPE+HDPE+PP	MCM-41	4:6	420	570	7.6	86.8	5.6	Wei et al. <sup>10</sup>
LDPE+HDPE+PP	MOR	1:9	360	570	5.4	91.6	3	Wei et al. <sup>10</sup>
LDPE+HDPE+PP	MOR	2:8	360	570	5.1	91.3	3.6	Wei et al. <sup>10</sup>
PE+PS+PP+PVC+PET+ABS	HZSM-5(V.P)	n.d.	500	n.d.	6	51	43	Macro et al. <sup>57</sup>
PE+PS+PP+PVC+PET+ABS	HZSM-5(L.P)	n.d.	500	n.d.	6.3	40	53.7	Macro et al. <sup>57</sup>
PE+PS+PP+PVC+PET+ABS	RED MUD	n.d.	500	n.d.	6	64	30	Macro et al. <sup>57</sup>
PE+PS+PP+PVC+PET+ABS	AlCl <sub>3</sub>	n.d.	500	n.d.	6.4	52.6	41	Macro et al. <sup>57</sup>
PE+PP+PS+PET+PVC	ZSM-5(Zeolite)	1:10	440	n.d.	4	40	56	Macro et al. <sup>57</sup>
HDPE	FCC	3:7	450	0.7	14.1	48.3	37.6	Mertinkat et al. <sup>60</sup>
HDPE	FCC	3:7	515	0.7	9.2	51.8	39	Mertinkat et al. <sup>60</sup>
PP	FCC	3:7	450	0.7	9.1	34.2	56	Lin et al. <sup>43</sup>
PE+PP+PS+PVC+PET	ZSM-5 Zeolite	1:10	440	1000	3.2	40.4	56.4	Lopez et al. <sup>33</sup>
PE+PP+PS+PVC+PET	ZSM-5 Zeolite	1:10	500	1000	1.8	58.4	39.8	Lopez et al. <sup>33</sup>
PE+PP+PS+PVC+PET	Red Mud	1:10	440	1000	2.2	21.6	76.2	Lopez et al. <sup>33</sup>
PE+PP+PS+PVC+PET	Red Mud	1:10	500	1000	1.7	41.3	57	Lopez et al. <sup>33</sup>
PE + PP+PS+PVC	FCC-RI	3:7	390	570	11.7	82.4	3.8	Lin et al. <sup>46</sup>
PE + PP+PS+PVC	Silicalite	3:7	390	570	85.1	13.5	1.4	Lin et al. <sup>46</sup>
PE + PP+PS+PVC	HUSY	HUSY	390	570	8.6	85.6	3.3	Lin et al. <sup>43</sup>
PE + PP+PS+PVC	ZSM-5	ZSM-5	390	570	6.4	88.3	3.4	Lin et al. <sup>43</sup>
PE + PP+PS+PVC	SAHA	SAHA	390	570	10.5	84.1	3.6	Lin et al. <sup>43</sup>
PE+PP+PS	USY	USY	360	570	8.8	87.5	3.7	Wei et al. <sup>10</sup>
PE+PP+PS	ZSM-5	ZSM-5	360	570	3.6	93.1	3.3	Wei et al. <sup>10</sup>
PE+PP+PS	MOR	MOR	360	570	5.5	90.2	4.3	Wei et al. <sup>10</sup>
PE+PP+PS	ASA	ASA	360	570	9.7	85.6	4.7	Wei et al. <sup>10</sup>
PE+PP+PS	MCM-41	MCM-41	360	570	7.1	87.3	5.6	Wei et al. <sup>10</sup>
PE, PP, PS and mixtures	Zeolites	n.d.	500-760	n.d.	0-6	1-72	31-92	Stelmachowski et al. <sup>27</sup>
P, PS and mixtures	Zeolites	n.d.	380-700	n.d.	0-21	6-55	31-71	Stelmachowski et al. <sup>27</sup>
PE	HZSM5	n.d.	400	n.d.	1	50	46	Stelmachowski et al. <sup>27</sup>
PE+PS+PP	Mgo+CaO	1:10	390-410	n.d.	6.4	3.7	86.5	Walendziewski <sup>56</sup>

V.P- Vapour phase contact, L.P-Liquid phase contact, n.d- not determined