

Recovery of Valuable Chemicals from High Density Polyethylene (HDPE) Polymer: a Catalytic Approach for Plastic Waste Recycling

Muhammad N. Almustapha and John M. Andrésen

Abstract—A high density polyethylene (HDPE) polymer was catalytically degraded using two sulfate modified Zirconium catalysts in a fixed-bed reactor at 400°C with the aim of converting plastic wastes to obtain valuable and recyclable liquid products. The TGA results revealed that the onset of degradation was moved from 420°C for HDPE alone to less than 300°C in the presence of the catalysts. The catalysts improved the polymer degradation by achieving high conversion of about 99.8%. The two catalysts appeared to promote different product composition. CAT1 (7%SO₃) was more selective to higher gaseous products (68%) and liquid (32%) of mainly aromatics, whereas CAT2 (3.5%SO₃) promoted high liquid products (about 53%) of mainly olefinic compounds. It can be concluded that the catalysts can be used for catalytic conversion of plastic wastes to obtain valuable products, most especially CAT2 (3.5%SO₃) which gave high liquid content that is composed of mainly olefinic, naphthenic and paraffinic compounds whose carbon number distribution is within the gasoline range. Thus, catalytic conversion using these catalysts may be used as an alternative method for recycling plastic wastes to more valuable and renewable energy sources.

Index Terms—Chemical recycling, fixed-bed reactor, HDPE polymer, plastic wastes, sulfate modified zirconium catalyst.

I. INTRODUCTION

The excellent properties of plastics such as light weight, durability and energy efficiency make them an indispensable part of our everyday activities [1], [2]. Thus, the world's annual plastic consumption increased dramatically from around 2 million tonnes in the 1950s to about 245 million tonnes in 2006 with a 10 % increase yearly [2]. Consequently, plastic wastes are increasing rapidly and contribute extensively to the problem of waste management. Various methods, such as land filling, mechanical, biological and other chemical recycling approaches are already in place, but still appear inadequate [3] or do not conform to current environmental regulations [2]. Therefore, there is the need for better approach to handle the menace without necessarily creating more problems.

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M. N. Almustapha is with Department of Pure and Applied Chemistry, Usmanu Danfodiyo University Sokoto, P.M.B 2346, Sokoto-Nigeria and currently a PhD candidate with the Department of Chemical and Environmental Engineering, University Nottingham, UK (email: enxmna@nottingham.ac.uk; nalmustapha@udusok.edu.ng).

J. M. Andresen is with the Department of Chemical and Environmental Engineering, University Nottingham, University Park, NG7 2RD, Nottingham, UK. (email: j.andresen@nottingham.ac.uk).

In view of this, catalytic conversion, which is a chemical recycling method that involves the conversion of polymers to recover useful products, may be the appropriate method [4].

Many studies on catalytic conversion of different types of plastics and polymers to different products, including chemicals and fuels using different type of catalysts have been published [5]-[7]. Different catalysts were reported for catalytic conversion of plastic wastes. These include ZSM-5 [7], [8], silica, alumina [9], basic catalysts, such as BaCO₃ [10], Bimetallic catalyst, Al-Zn composite [11], FCC catalyst [12], [13], and mesoporous catalysts, such as Al-MCM-41 [14]. Zeolites based catalysts are the most widely reported for this process. They work effectively in terms of high conversion of plastic wastes at lower temperature and decrease the activation energy. However, these catalysts are associated with high gaseous products with little liquid yield which also has a high aromatic content [14]. Also, they are very expensive and require long residence time. Thus, the cost of production involving these catalysts may be generally prohibitive.

This work is aimed at catalytically converting high density polyethylene (HDPE) polymer into liquid products that could be used as fuel and feed-stock for chemical industries on sulfate modified zirconium catalyst using a fixed-bed reactor. Emphasis will be given to high conversion and selectivity to liquid products with less aromatic content, at low temperature. This will provide an option for plastic waste recycling which is sustainable and cost-effective.

II. MATERIALS AND METHOD

A. HDPE Polymer and Catalysts

A model high density polyethylene (HDPE) polymer sample with density of 0.952 gmL⁻¹ and degradation index 42g/10min was obtained from Sigma-Aldrich, UK. The physical and chemical properties of the polymer are given in Table I. The two catalysts used were CAT1 (7%SO₃) and CAT2 (3.5%SO₃) with particle size of 105-125 microns. Prior to use, these catalysts were calcined at 550°C for three hours and then cool down in a desiccator. These catalysts were obtained from MEL chemicals, UK.

B. Experimental Procedure and Analysis

1) Thermogravimetric analysis (TGA)

TG analysis was conducted on the polymer samples with and without the catalyst. A Pyris 1 Thermal Gravimetric analyzer (TGA1), a product of Perkin-Elmer was used at a heating rate of 10oC/min from 35 to 900OC in a nitrogen gas atmosphere with a flow rate of 20 ml/min.

The HDPE polymer and its mixture with catalysts were

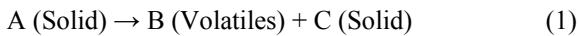
weighed between 20-30 mg and placed in quartz crucibles.

TABLE I: CHARACTERISTICS OF THE HDPE POLYMER USED
CHARACTERISTICS

Proximate composition	Wt (%)
Volatile matter	96.83
Ash	3.17
Elemental composition	(Wt.% dry ash free)
C	85.7
H	14.1
N	0.00
S	0.00
Physical properties	
Density	0.952 gmL ⁻¹
Degradation index	42g/10min
Colour	White
Form	Pellet
Polymer size used	75-100 micron

2) Kinetic Parameter estimation using TGA data

Kinetic study of the thermal and catalytic decomposition of plastic polymer was determined from Thermogravimetric analysis (TGA) data. The activation energy and pre-exponential factors were determined based on the thermal decomposition of polymers from equation1.



The rate of polymer degradation is considered to be proportional to the concentration of reactants defined in equation 2 [15]. Where α is the extent of polymer conversion with m_0 ; m_i and m_f are the initial, actual and final weight of the HDPE polymer, respectively, t is the time taken, β is the heating rate, T is the temperature and R is the gas constant whose value is $8.314 \text{ kJ mol}^{-1} \text{ K}^{-1}$.

$$r = -\frac{d\alpha}{dt} = kf(\alpha) \quad (2)$$

The extend of conversion (α) is given

$$\alpha = \frac{m_0 - m_i}{m_0 - m_f} \text{ where } f(\alpha) = (1-\alpha)^n \quad (3)$$

By the Arrhenius equation, $k = Ae^{-\frac{Ea}{RT}}$, Equation 2 becomes:

$$\frac{d\alpha}{dt} = Ae^{-\frac{Ea}{RT}} * (1-\alpha)^n \quad (4)$$

And for a constant heating rate β , ($\beta = \frac{dT}{dt}$), equation (4)

becomes:

$$\frac{d\alpha}{dT} = \frac{A}{\beta} e^{-\frac{Ea}{RT}} * (1-\alpha)^n \quad (5)$$

By separating variables, rearranging and integrating equation (5), the expression below is obtained:

$$\frac{1-(1-\alpha)^{1-n}}{1-n} = \frac{A}{B} \int_0^T e^{-\frac{Ea}{RT}} dT \quad (6)$$

However, as $\int_0^T e^{-\frac{Ea}{RT}} dT$ has no exact integral, $e^{-\frac{Ea}{RT}}$ can be expressed as an asymptotic series and integrated by ignoring high-order terms. Thus, equation (7) emerged.

$$\frac{1-(1-\alpha)^{1-n}}{T^2(1-n)} = \frac{ART^2}{\beta E} \left[1 - \frac{2RT}{E} \right] e^{-\frac{Ea}{RT}} \quad (7)$$

By taken the natural logarithm of both sides of equation (7), equation (8) emerged.

$$\ln \left[\frac{1-(1-\alpha)^{1-n}}{T^2(1-n)} \right] = \ln \left[\frac{AR}{\beta E} \left[1 - \frac{2RT}{E} \right] \right] - \frac{Ea}{RT} \quad (8)$$

But generally it is assumed $\frac{RT}{E} \ll 1$ and $1 - \frac{2RT}{E} \approx 1$

Thus, equations (9) and (10) for n=1 and n=2 respectively, emerged:

$$\ln \left[\frac{1-(1-\alpha)^{1-n}}{T^2(1-n)} \right] = \ln \left[\frac{AR}{\beta E} \right] - \frac{Ea}{RT} \quad (n \neq 1) \quad (9)$$

and

$$\ln \left[-\frac{\ln(1-\alpha)}{T^2} \right] = \ln \left[\frac{AR}{\beta E} \right] - \frac{Ea}{RT} \quad (n = 1) \quad (10)$$

In this work, a first order (n=1) has been selected, as it has already been established that polymer degradation obeys first order kinetics [17]. Therefore, a plot of $\ln \left[-\frac{\ln(1-\alpha)}{T^2} \right]$ versus $\frac{1}{T}$ was used to calculate the apparent kinetic parameters. The plot gave a straight line with $-Ea/R$ as slope. The value of the slope obtained was used to calculate the activation energy and the pre-exponential factor (A) from the intercept on the y axis.

3) Catalytic Degradation

The catalytic degradation of the HDPE polymer was carried out in a horizontal stainless steel fixed-bed tube (Fig. 1), in which the polymer and the catalyst at appropriate ratio were mixed thoroughly and transferred into a crucible boot.

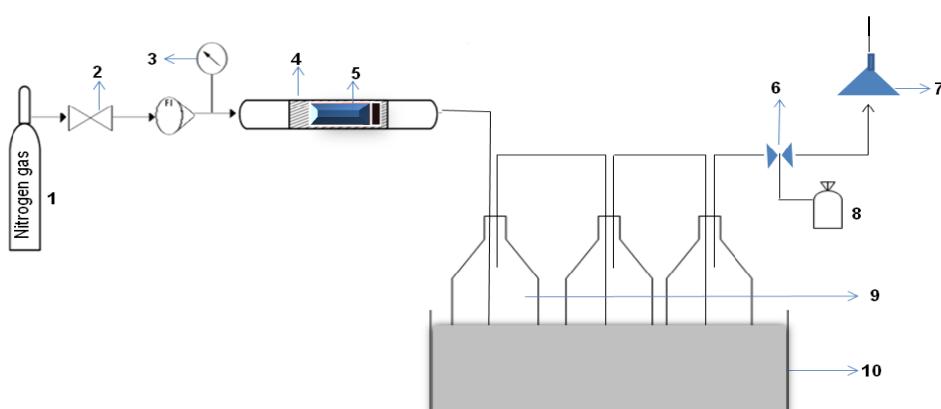


Fig. 1. Schematic diagram of fixed-bed reactor used for catalytic degradation of HDPE plastic polymer; 1. Nitrogen gas supply, 2. Mass flow control, 3. Gas flow meter, 4. Reactor, 5. HDPE + catalyst, 6. Two-way control valve 7. Exhaust gas trap, 8. Gas bag, 9. Liquid trap, 10. Cooling trap made up of ice bath.

The crucible and contents were then placed in the tube and heated to 400°C at a heating rate approximately 20°C min⁻¹ using nitrogen of flow rate 30 cm³ min⁻¹ to purge the products formed. Prior to heating, a nitrogen gas was passed through the reactor for 20 min to make the environment inert. The condensable liquid was collected through special cooling tarps. The gaseous products were collected using gas bags.

The percentage yield of liquid product was calculated as the mass of a liquid collected divided by the initial mass of the polymer while that of coke (residue) yield was calculated by dividing the mass of unconverted polymer (minus the catalyst weight) by the original polymer weight.

4) Liquid Products analysis

The liquid products were analysed with Variant CP-3800 Gas Chromatogram interfaced to a 1200 Quadrupole mass spectrometer. About 1 µl of the oil dissolved in dichloromethane (DCM) was injected. The eluted components were monitored in both full scan mode and selected ion monitoring. Each peak was identified based on the MS software library.

5) Gaseous Products Analysis

The gaseous products were analysed using a Carlo Egba HRGC 5300 Gas Chromatograph fitted with FID and TCD detectors operating at 200°C and 180°C, respectively. The hydrocarbon gases were analysed by FID using a Chrompak CPPorapak plot Q capillary column (27.5 m x 0.32 mm, 10 µm film thickness) by injecting 10 µl of gas sample. Helium was the carrier gas used and an oven temperature programme of 70°C (hold 2 min) to 90°C (3 min) at 40°C min⁻¹, then to 140°C (3 min) at 40°C min⁻¹ and finally to 180°C (49 min) at 40°C min⁻¹.

III. RESULTS AND DISCUSSION

A. Thermogravimetric Analyses (TGA)

Fig. 2 shows the TGA curves illustrating the HDPE polymer degradation in the presence of the two catalysts CAT1 (7%SO₃) and CAT2 (3.5% SO₃) and HDPE alone. Comparing the curves from Fig. 1, it can be deduced that with CAT1 (7%SO₃) and CAT2 (3.5% SO₃), the degradation commenced at considerably lower temperature even below 200°C compared to 420°C for HDPE alone.

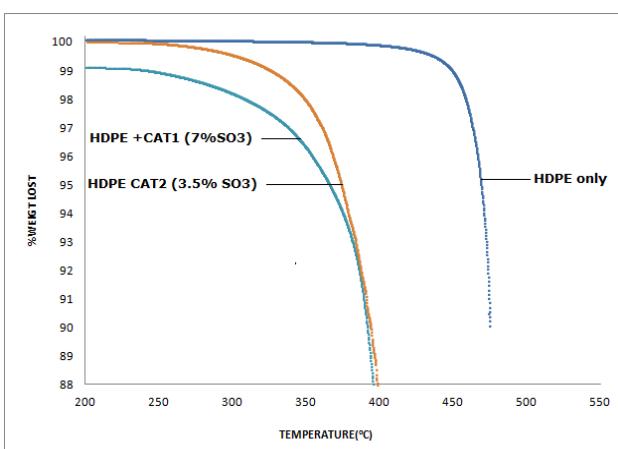


Fig. 2. TGA curves comparing HDPE polymer degradation with and without any catalysts.

Also about 92% conversion was achieved at 460°C for both catalysts unlike only 3% conversion for HDPE alone. This indicates that CAT1 (7%SO₃) and CAT2 (3.5% SO₃) are very active catalysts and therefore suitable for polymer degradation.

B. Kinetic Studies

Table II gives the summary of the kinetic parameters calculated where the apparent activation energy of the HDPE polymer was found to be 342 kJmol⁻¹. This value is within the range of values reported elsewhere [15], [16]. The addition of the catalysts shows a dramatic reduction in the activation energies down to 132.61 and 159.996 kJmol⁻¹ when CAT1 (7%SO₃) and CAT2 (3.5%SO₃) are used, respectively. This indicates that, these catalysts enhanced the reaction rate by almost twofold. They also played an important role in product selectivity, as confirmed from the products of catalytic degradation using a fixed-bed reactor.

TABLE II: APPARENT KINETIC PARAMETERS DERIVED FROM TGA DATA

Sample	Activation energy, Ea (kJmol ⁻¹)	Frequency Factor, A (S ⁻¹)	Correlation coefficient (R ²)
HDPE alone	342.95	5.22 X 10 ¹⁹	0.9955
HDPE+CAT1(7%SO ₃)	132.61	1.46 X 10 ⁶	0.9924
HDPE+ CAT2(3.5%SO ₃)	159.96	2.22 X 10 ⁸	0.9959

C. Conversion, Yield and Selectivity

The results of the catalytic polymer degradation which include overall conversion, products yield (liquid and gases), are summarised in Table III. From Table III, it is evident that CAT1 (7%SO₃) and CAT2 (3.5% SO₃) give prominent conversion of almost 99.9% and in terms of products yield. However, a high liquid yields can be observed when CAT2 (3.5% SO₃) is used whereas CAT1 (7%SO₃) gave high gas yields. This indicates that CAT1 (7% SO₃) has high activity which promote gaseous product than CAT2 (3.5 SO₃) and might be related to its high acidity which probably led to end-chain scission that gave rise to light hydrocarbon [17], [18]. However, CAT2 (3.5% SO₃) gave an indication of better selectivity to liquid which may be attributed to low sulfate content leading to moderate acidity.

TABLE III: COMPARISON OF THE PRODUCTS YIELD OF HDPE POLYMER CATALYTIC DEGRADATION AT 400°C.

Parameters	CAT1 (7%SO ₃)	CAT 2 (3.5%SO ₃)
% Conversion	99.98	99.96
% Oil Yield	34.31	53.00
% Gas yield	65.68	46.98
% Residue	0.01	0.02

Although optimisation of various reaction parameters have not been conducted, these catalysts are however, promising going by the highest conversion of about 99% achieved at just 400°C in 30 minutes only.

Fig. 3 compares chromatograms of the oils obtained from catalytic degradation of HDPE plastic polymer using the two catalysts. From the Figure, different peaks which are representing different compounds in the range of C7-C12 were detected. This indicates that the composition of the oil obtained using both catalysts differ but still remain within the gasoline range. And that the oil is composed of a broad

mixture of hydrocarbon compounds consisting of mainly paraffinic, olefins naphthenic and aromatic which is in line with the GC/MS analysis reported from previous works published using other catalysts [10].

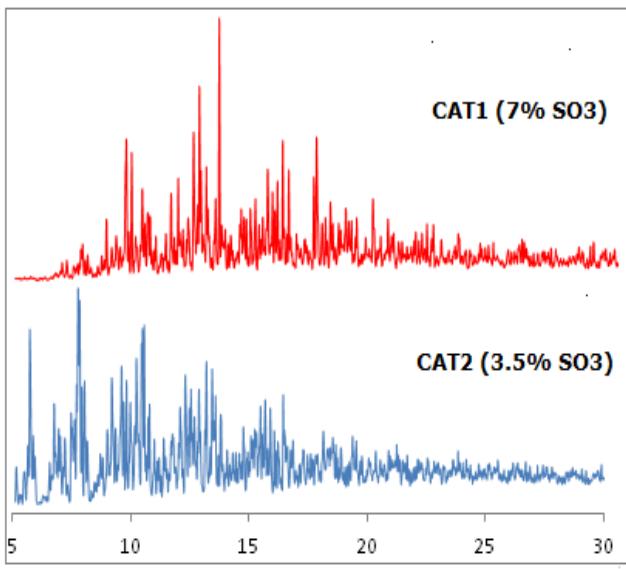


Fig. 3. GC/MS chromatograms of the liquid products

Interestingly C7, C12, C13 and C14 compounds were all detected in oil from CAT2 (3.5% SO₃) but none was found in the oil from CAT1 (7% SO₃). However, it can be seen from Table IV that the composition of the liquid products from CAT1 (7% SO₃) contains mainly aromatics (45%) whereas CAT2 (3.5% SO₃) contains largely olefinic hydrocarbon (65%). This can also be observed from Fig. 4, which showed the colours of the liquid products obtained from the two catalysts. Liquid form CAT1 (7% SO₃) which contained much aromatic compounds is darker in colour than that of CAT2 (3.5% SO₃) which contains no aromatic compound.

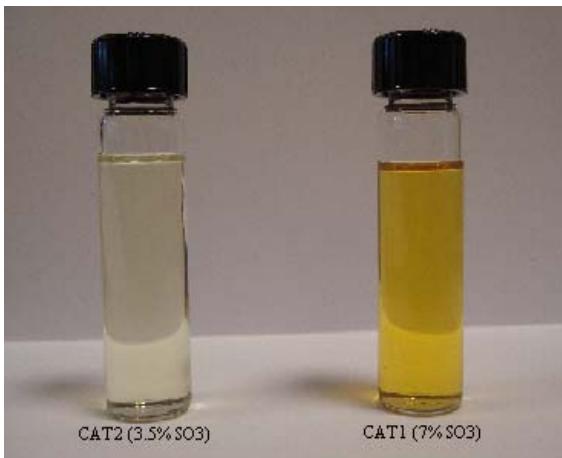


Fig. 4. Picture of the liquid products from the two catalysts used

This indicates that CAT1 (7% SO₃) is possibly promoting mainly aromatic compounds through aromatization reaction via dehydrocyclisation of the hydrocarbon fragments formed. Whereas CAT2 (3.5% SO₃) accelerates the formation of largely olefinic compounds but inhibits aromatisation which could have resulted from isomerisation of the carbocation fragment via hydrogen atom shift that may give rise to unsaturated hydrocarbons [19].

Composition	CAT1(7%SO ₃)	CAT2(3.5%SO ₃)
Aromatics	45%	0
Olefinic	25%	65%
Naphthenic and Aliphatic	30%	35

In overall, this indicates that, the liquid products obtained from the two catalysts could be used as a transport fuel after some minor modifications. The liquid product from CAT1 (7% SO₃) which contains high amount of aromatic and some naphthenic compounds could be a good motor fuel since aromatic and naphthenic compounds improve the quality of gasoline by increasing the Octane number. While for oil obtained using CAT2 (3.5% SO₃) which has high olefinic and some paraffinic and naphthenic compounds, could be in addition used as a feedstock for petrochemical industries. Olefinic compounds are industrially more attractive than even the pure saturated compounds [20], as they are intermediaries of many valuable and expensive chemicals. Therefore, both catalysts promote liquid products from the plastic wastes that are of commercial and industrial benefits.

D. Gaseous Products Analysis

Fig. 5 is a GC chromatogram of the gaseous products showing peaks representing the components of the gas from each catalyst. From the figure, it can be seen clearly that the gases from CAT1 and CAT2 contains broad mixture of gases ranging from C1-C7. However, C3 (propane and propene), C4 (n-butane, iso-butane, bute-1-ene, bute-2-ene) and isobutene), and C5 (n-pentane, pent-1-ene and isopentane) are more pronounced. Although, both C1 (Methane) and C2 appear very negligible, the gaseous products from both the catalysts are still of commercial value and could be used as a source of energy for heating the reactors thereby reducing the cost of the process.

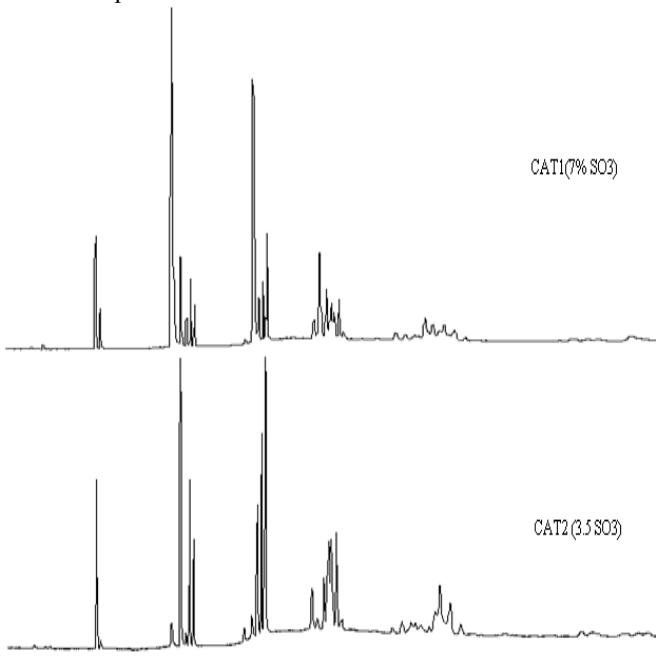


Fig. 5. GC chromatograms of the gaseous products

IV. CONCLUSIONS

The catalytic degradation of HDPE polymer was found to be a useful method of managing plastic wastes by adding value to it, as valuable products were obtained. The kinetic

results from TGA revealed that these catalysts improved the reaction rate probably by suppressing the bond energy and subsequently reducing the activation energies from 342 kJmol⁻¹ to 132.61 and 159.96 KJmol⁻¹ for CAT1 (7%SO₃) and CAT2 (3.5% SO₃) respectively. The catalysts also improved the polymer degradation greatly by achieving high conversion at a temperature of 400°C. The liquid product yields are unprecedented more especially from CAT2 (3.5% SO₃). The liquid products composition varied greatly depending on the amount of sulfate in the catalyst. High percentage conversion, 99.8 and 99.96 % were achieved for CAT1 (7%SO₃) and CAT2 (3.5% SO₃), respectively. However, CAT1 (7% SO₃) appears to be favouring high yield of gaseous products (68%), and the liquid products (32%) composition is mainly aromatics. CAT2 (3.5% SO₃) promotes high liquid products (about 53%) whose composition is mainly olefinic compounds, and some gaseous products (about 47%). The two catalysts seemed to be following different mechanisms.

Consequently, the high conversion obtained by the catalysts indicates that, the catalysts can be used efficiently even at industrial scale. Also, having all the liquid products with carbon number distribution within the gasoline range which consist of mainly aromatic and olefinic compounds for CAT1 (7%SO₃) and CAT2 (3.5% SO₃), respectively indicates the applicability of the products both as fuel and industrial raw material. Therefore, it can be deduced that this catalytic approach would offer a great deal of plastic polymer recycling and obtain many valuable and renewable energy options. Thus, can be used as an alternative recycling method for converting plastic waste to valuable energy sources

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REFERENCES

- [1] Singhabhandhu, and T, Tezuka. "The waste-to-energy framework for integrated multi-waste utilization: Waste cooking oil, waste lubricating oil, and waste plastics". *Energy*, vol. 35, pp. 2544-2551, March 2010.
- [2] A. K. Panda, R. K. Singh and D. K. Mishra. "Thermolysis of waste plastics to liquid fuel. A suitable method for plastic waste management and manufacture of value added products- A world prospective". *Renewable & Sustainable Energy Reviews*, vol. 14, pp. 233-248, 2010.
- [3] H. T. Shent, R. J. Pugh and E. Forssberg. "A review of plastics waste recycling and the flotation of plastics". *Resources Conservation and Recycling*, vol. 25, pp. 85-109, 1999.
- [4] Y. H. Lin, P. N. Sharratt, A. A. Garforth, and J. Dwyer. "Catalytic conversion of polyolefins to chemicals and fuels over various cracking catalysts". *Energy & Fuels*, vol. 12, pp.767-774, 1998.
- [5] Y. H. Lin, M. H. Yang, T. T. Wei, C. T. Hsu, K. J. Wu, and S. L. Lee. "Acid-catalyzed conversion of chlorinated plastic waste into valuable hydrocarbons over post-use commercial FCC catalysts". *Journal of Analytical and Applied Pyrolysis*, vol. 87, pp. 154-162, 2010.
- [6] Y.H. Lin. "Production of valuable hydrocarbons by catalytic degradation of a mixture of post-consumer plastic waste in a fluidized-bed reactor". *Polymer Degradation and Stability*, vol. 94, pp. 1924-1931, 2009.
- [7] D. W. Park, E. Y. Hwang, J. R. Kim, J. K. Choi, Y. A. Kim, and H. C. Woo "Catalytic degradation of polyethylene over solid acid catalysts". *Polymer Degradation and Stability*, vol. 65, pp.193-198, 1999.
- [8] N. Miskolczi, L. Bartha, G. Deák, B. Jóver, and D. Kalló. "Thermal and thermo-catalytic degradation of high-density polyethylene waste". *Journal of Analytical and Applied Pyrolysis*, VOL. 72, PP. 235-242, November, 2004
- [9] J. Shah, M. R. Jan, F. Mabood, and F. Jabeen. "Catalytic pyrolysis of LDPE leads to valuable resource recovery and reduction of waste problems". *Energy Conversion and Management*, vol. 51, pp.2791-2801, 2010.
- [10] M. R. Jan, J. Shah, and H. Gulab. "Catalytic degradation of waste high-density polyethylene into fuel products using BaCO₃ as a catalyst". *Fuel Processing Technology*, vol. 91, pp.1428-1437, 2010.
- [11] C. Tang, Y. Z. Wang, Q. Zhou, and L. Zheng. "Catalytic effect of Al-Zn composite catalyst on the degradation of PVC-containing polymer mixtures into pyrolysis oil". *Polymer Degradation and Stability*, vol. 81, pp. 89-94, 2003.
- [12] N. Miskolczi, L. Bartha, and G. Deák. "Thermal degradation of polyethylene and polystyrene from the packaging industry over different catalysts into fuel-like feed stocks". *Polymer Degradation and Stability*, vol. 91, pp. 517-526, 2006.
- [13] W.C. Huang, M. S. Huang, C.F. Huang, C. C. Chen, and K. L. Ou. "Thermochemical conversion of polymer wastes into hydrocarbon fuels over various fluidizing cracking catalysts". *Fuel*, vol. 89 pp. 2305-2316, 2010
- [14] B. Saha, A. K. Chowdhury, and A. K. Ghoshal. "Catalyzed Decomposition of Propylene and Hybrid Generic Algorithm for Kinetics Analysis". *Applied Catalysis B: Environmental*, vol. 83, pp. 265-276, 2008.
- [15] J. Guo, and A. C. Lua. "Kinetic study on pyrolytic process of oil-palm solid waste using two-step consecutive reaction model". *Biomass and Bioenergy*, vol. 20 pp. 223-233, 2001.
- [16] J. Yang, R. Miranda, and C. Roy. "Using the DTG curve fitting method to determine the apparent kinetic parameters of thermal decomposition of polymers". *Polymer Degradation and Stability*, vol. 73, pp. 455-461, 2001.
- [17] A. Aboulkas, K. El-harfi, and A. El-Bouadili. "Thermal degradation behaviours of polyethylene and polypropylene. Part I: Pyrolysis kinetics and mechanisms". *Energy Conversion and Management*, vol. 51, pp. 1363-1369, 2010.
- [18] N. Miskolczi, A. Angyal, L. Bartha, and I. Valkai. "Fuels by pyrolysis of waste plastics from agricultural and packaging sectors in a pilot scale reactor". *Fuel Processing Technology*, vol. 90, pp. 1032-1040, 2009.
- [19] J. Aguado, D. P. Serrano, J. M. Escola, and A. Peral, "Catalytic cracking of polyethylene over zeolite mordenite with enhanced textural properties". *Journal of Analytical and Applied Pyrolysis*, vol. 85, pp. 352-358, 2009.
- [20] A. G. Buekens, and H. Huang. "Catalytic plastics cracking for recovery of gasoline-range hydrocarbons from municipal plastic wastes". *Resources Conservation and Recycling*, vol. 23, pp.163-181, 1998.