

Synthesis of C5-C22 Hydrocarbon Fuel From Ethylene-Based Polymers

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Abstract— The current study tested the hypothesis as to whether or not polyethylene-based plastic can be converted to liquid fuel by thermal catalytic cracking over metal oxide catalysts, including $\text{Ca}(\text{OH})_2$, Al_2O_3 , and ZnO . To determine the optimum condition for the highest yield of low molecular weight (C5-C22, MW=100-300) liquid fuel production, the catalyst-to-polymer ratio was investigated at various temperature and reaction times. The initial liquid product obtained from each catalyst was further cracked to yield hydrocarbons of lower molecular mass. The obtained final products were analyzed by gas chromatography-mass spectrometry (GC-MS), high performance liquid chromatography (HPLC), infrared resonance (FT-IR), and elemental analysis (EA). The GC/MS analysis demonstrated that the fuel obtained had constituents ranging from carbon numbers of 5-22. The FT-IR spectra showed the expected functional group and the element analyzer indicated the gross and net heating values of the fuel to be within the range 61-383 MJ/Kg. Comparative analysis showed that $\text{Ca}(\text{OH})_2$ has the highest total conversion yield followed by Al_2O_3 and then ZnO .

Index Terms—Catalytic conversion, gasoline, hydrocarbon fuel, metal oxide, plastic, polyethylene, thermal cracking

1 INTRODUCTION

ETHYLENE-BASED polymers are vital in the production of film wraps, plastic bags, electrical insulators, and bottles. The demand for ethylene-based materials is growing fast. World plastic production data shows an increase from 1.7 million tons in 1950 to 280 million tons in 2011 [1].

With increased consumption and disposal of plastic materials, the need to manage plastic wastes is apparent. Plastic waste materials are largely composed of high density and low density polyethylene (HDPE/LDPE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), polyethylene terephthalate (PET) and acrylonitrile butadiene styrene (ABS). We hypothesize that thermal catalytic conversion of waste plastics will generate low molecular weight hydrocarbon fuel. Our aim is to create an alternative energy source as well as ensure the protection of the environment through effective waste collection and conversion [2], [3]. HDPE and LDPE are identified as suitable plastic waste materials for pyrolysis and are the most commonly found plastic materials littered around the world [4]. Polyethylene is resistant to thermal degradation and catalysts are required to enhance pyrolysis. Pyrolysis of LDPE using a catalyst is reported to have a high conversion rate of 86%

[4]. Various catalysts, including silica alumina and zeolites, have been reported to give high yields of liquid fuel through the thermo-catalytic conversion, and BaCO_3 is reported to have a low production of wax during the process [5], [6], [7], [8], [9].

We tested our hypothesis further that the liquid collected after catalytic conversion was distilled to produce hydrocarbon fractions that have similar properties as gasoline and diesel. However, various factors affect the conversion of polyethylene-based polymers to liquid fuels. We found that an important factor is the catalyst-to-polymer ratio. Catalyst-to-polymer ratio controls yield and optimum liquid hydrocarbon products using various catalysts [5], [10]. The current studies tested catalyst-to-polymer ratio and reaction conditions to maximize hydrocarbon liquid yield. Our data demonstrated that reaction temperature affected the product yield with high temperature (450°C - 550°C) to be ideal for total conversion; however, various catalysts accelerated reactions under low reaction temperature (250°C) [4], [5], [10], [11], [12]. The current study tested the hypothesis with the following aims: (1) to determine the catalytic conversion of carbon-carbon bond cleavage of polymers under 200°C and within a 1-hour time frame using several catalysts, including $\text{Ca}(\text{OH})_2$, ZnO and Al_2O_3 ; (2) to determine the optimum catalyst-to-polymer ratio at which the maximum yield of C6-C16 hydrocarbon can be obtained; (3) to determine distillation by-products from fuel produced from LDPE/HDPE/PET. The by-products in question include terephthalic acid and benzoic acid that are biodegradable. Our data demonstrated that polymer waste can be converted into low molecular weight hydrocarbons, including gasoline and diesel, by thermal catalytic cracking.

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2 MATERIALS AND METHODS

2.1 Reaction Conditions

LDPE packaging material was obtained from the local market and shredded into small pieces. The pieces were weighed and prepared for the pyrolysis. In all pyrolysis experiments, the catalysts used included Al_2O_3 , ZnO , and $\text{Ca}(\text{OH})_2$ obtained from Acros Organics, Kermel and BDH Chemicals Ltd., respectively.

The catalytic pyrolysis reaction was carried out in a batch Pyrex round-bottom glass. A fixed amount of the LDPE and catalyst was weighed and placed in the reactor. The glass reactor with known weight of feedstock was placed on a 200-Watt heating mantle and heated to 200 °C. The reactor delivery tube was connected to a condenser leading to the receiving flask. The products from the reaction were in the form of non-condensable gases, condensable oil, wax and solid residues. Condensable oil and wax were collected while the solid residues were left in the bottom of the reactor.

The condensable liquid obtained from catalytic pyrolysis was placed in a fractional distillation apparatus and distilled into various fractions at boiling point ranges of gasoline and diesel. The experiment was performed using catalyst-to-polymer ratios from 1:1 to 1:5.

2.2 Analysis

The total percent conversion was calculated as follows:

$$\text{Total \% conversion} = (\text{weight of LDPE waste material} - \text{weight of residue}) \times 100 / \text{weight of LDPE waste material} \quad (1)$$

The liquid percent conversion was calculated as follows:

$$\text{Liquid \% conversion} = \text{weight of liquid} \times 100 / \text{weight of LDPE waste material} \quad (2)$$

Thermo Nicolet IR100 FT-IR was used to determine the functional groups in the various distillates recovered after fractionation. Agilent 7890A GC with 5975C inert MSD was used to analyze the components of the fractions. The oven of the GC operated at a pressure of 7.070 psi and had an initial temperature of 40 °C for 10 minutes and was gradually increased to 300 °C at a rate of 10 °C/min.

3 RESULTS AND DISCUSSION

3.1 Effect of Catalyst Ratio

The optimum ratio was determined by testing various catalyst-to-polymer ratios (1:1, 1:2, 1:3, 1:4 and 1:5) for maximum liquid conversion. Experiments showed that increased catalyst downregulated liquid conversion [13]. Catalyst:polymer ratio of 1:4 appeared to yield the optimum total conversion as well as optimum liquid conversion as shown in Fig. 1.

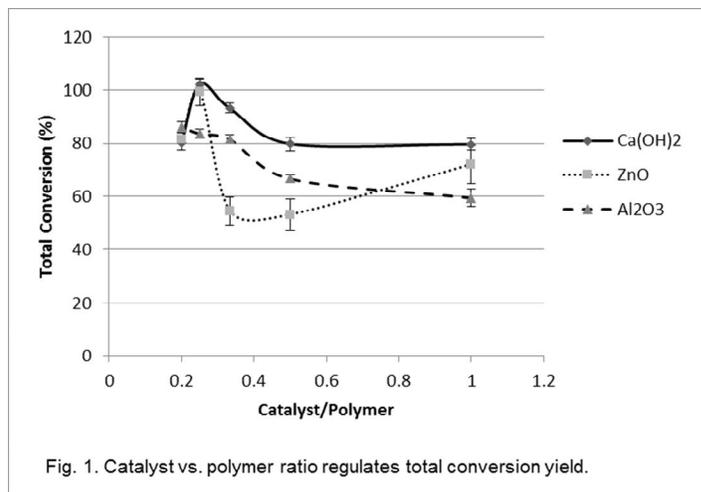


Fig. 1. Catalyst vs. polymer ratio regulates total conversion yield.

3.2 Fractional Distillation

The first liquid products were separated into three fractions based on boiling point. Two distillates were obtained from each of the parent oils for a specific catalyst type. Table 1 presents the boiling temperature, color, and the respective mass (as a per cent of parent mass) of distillate fractions obtained from the parent oil for each catalyst. Catalyst-to-polymer ratio also affected total liquid conversion yield as shown in Fig. 2.

TABLE 1
DISTILLATES OF PARENT OIL AND THEIR CORRESPONDING MASS PERCENTAGE

Catalyst	Mass of parent oil (g)	Distillate type	Mass of distillate (g)	Mass (%)
$\text{Ca}(\text{OH})_2$	21.8	first distillate (90-200 °C) light yellow	10.4	47.7
		second distillate (200-230 °C) dark yellow	10.5	48.2
Al_2O_3	11.9	first distillate (30-100 °C) dark yellow	16.3	82.9
		second distillate (100-230 °C) dark brown	2.36	12.0
ZnO	19.6	first distillate (80-112 °C) light yellow	9.47	79.9
		second distillate (112-230 °C) dark brown	1.92	16.2

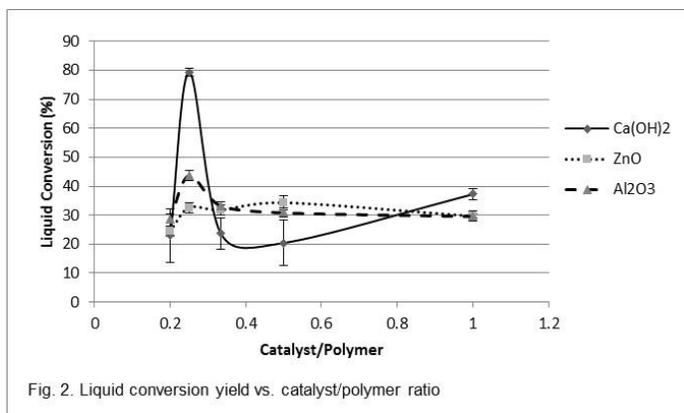


Fig. 2. Liquid conversion yield vs. catalyst/polymer ratio

FT-IR spectrum analysis showed that the fuel fractions that were obtained from the parent oil catalyzed by $\text{Ca}(\text{OH})_2$ had the following functional groups: cis-RCH=CHR, =C-H (trans), =CH₂ (trans), -OH bending, -CH₃ bend, -C=C-, C_{sp3}-H and C_{sp2}-H (Table 2). Previous reports from others also showed the domination of olefins in liquid hydrocarbons by solid base catalysis [14].

TABLE 2

FTIR SPECTRA OF FRACTIONS FROM $\text{Ca}(\text{OH})_2$ CATALYSIS

Peak number	Wave number (cm ⁻¹)	Functional group
1	3077.95	C _{sp2} -H
2	2957.65	C _{sp3} -H
3	2925.55	C _{sp3} -H
4	2855.01	C _{sp3} -H
5	1641.01	-C=C-
6	1463.74	-CH ₃
7	1378.01	-OH bending
8	992.01	-HC=CH ₂ -
9	965.20	-HC=CH ₂ - (trans)
10	909.37	-HC=CH ₂
11	721.88	RCH=CHR (cis)

Analysis from fuel fractions obtained by Al_2O_3 catalysis displayed the following functional groups: C_{sp3}-H, Si-H, C=C, -CH₃ bend, -OH bend, cis-RCH=CHR, -NH₂ (Table 3).

TABLE 3

FTIR SPECTRA OF FRACTIONS FROM Al_2O_3 CATALYSIS

Peak number	Wave number (cm ⁻¹)	Functional group
1	2931.21	C _{sp3} -H
2	2882.77	C _{sp3} -H
3	2348.63	Si-H
4	1739	C=O
5	1557.99	-NH ₂
6	1460	-CH ₃
7	1399.21	-OH bending
8	720	RCH=CHR (cis)

IR spectroscopy carried out on the fractional distillates obtained from ZnO catalysis indicated the following functional

groups: C_{sp3}-H, Si-H, -C=C-, -CH₃ bend, -OH bend, cis-RCH=CHR, -NH₂, -HC=CH₂- (trans), (Table 4).

TABLE 4

FTIR SPECTRA OF FRACTIONS FROM ZnO CATALYSIS

Peak number	Wave number (cm ⁻¹)	Functional group
1	3077.13	C _{sp2} -H
2	3013.69	C _{sp2} -H
3	2931.21	C _{sp3} -H
4	2882.77	C _{sp3} -H
5	1648.55	-C=C-
6	1548.96	-NH ₂
7	1464.90	-CH ₃
8	1376.35	-OH bending
9	964.27	-HC=CH ₂ - (trans)
10	909.23	-HC=CH ₂
11	721.88	RCH=CHR (cis)

Gas chromatography and mass spectrometry (GC-MS) analysis revealed hydrocarbon chains ranging from C₅-C₁₅ in the first (90–200 °C) and second (200–230 °C) distillate fractions from $\text{Ca}(\text{OH})_2$ catalysis (Table 5). Analysis of first (30–100 °C) and second (100–230 °C) distillate fraction from Al_2O_3 indicated hydrocarbon chains from C₅-C₁₆. The fraction obtained from the first (80–112 °C) and second (112–230 °C) distillate of ZnO catalysis contained hydrocarbons ranging from C₅-C₂₂.

It was observed that the chromatogram obtained from the 90–200 °C distillate via $\text{Ca}(\text{OH})_2$ catalysis revealed a higher relative abundance of light hydrocarbons over heavier types, while the chromatogram of the second distillate (200–230 °C) showed predominantly heavier hydrocarbons. We attribute this result to the fact that the heavier fractions and higher boiling hydrocarbons, including octadecane and nonadecane, were obtained in the second distillate. Similarly, the chromatograms of the first distillates via Al_2O_3 and ZnO catalysis showed that the relative abundance of the light hydrocarbons was greater compared to the heavier types (Table 6, 7). The second distillates showed high percentage of heavier hydrocarbon chains as expected.

TABLE 5

HYDROCARBON COMPOSITION OF FUEL DISTILLATES BY $\text{Ca}(\text{OH})_2$

Compound Name	Compound Formula	Molecular Weight	%
1-Decene	C ₁₀ H ₂₀	140.27	9.02
1-Decyne	C ₁₀ H ₁₈	138.25	0.07
1-Dodecyne	C ₁₂ H ₂₂	166.30	0.03
2-nonene	C ₉ H ₁₈	126.24	2.42
3-nonene	C ₉ H ₁₈	126.24	1.93
(E)-Cyclopropane, 1-methyl, 2-pentyl	C ₉ H ₁₈	126.24	1.46
(E,Z)-Propylidencyclohexane	C ₉ H ₁₆	124.22	0.02
7-Formylbicyclo [4.1.0] heptane	C ₈ H ₁₂ O	124.18	0.07
3, 4-Octadiene	C ₈ H ₁₄	110.20	0.02
3-Dodecyne	C ₁₂ H ₂₂	166.30	0.01

7-methyl-3,4-octadiene	C ₉ H ₁₆	124.22	0.09	1-Decanol	C ₁₀ H ₂₂ O	158.28	0.28
3-Decen-1-ol	C ₁₀ H ₂₀ O	156.27	0.02	2-Tridecene	C ₁₃ H ₂₆	182.35	0.04
(Z)-Ethylidene cycloheptane	C ₉ H ₁₆	124.223	0.30	Cyclodecane, methyl-	C ₁₁ H ₂₂	154.29	0.01
Undecane	C ₁₁ H ₂₄	156.31	9.29	2,3,5-trimethyl decane	C ₁₃ H ₂₈	184.36	0.72
1-hexyl-2-propyl trans-cyclopropane	C ₁₂ H ₂₄	168.32	0.22	Cyclotetradecane	C ₁₄ H ₂₈	196.22	0.20
2-Tridecene	C ₁₃ H ₂₆	182.35	2.89	Dodecane	C ₁₂ H ₂₆	170.33	1.21
Cyclotetradecane	C ₁₄ H ₂₈	196.37	0.36	Cyclotetradecane	C ₁₄ H ₂₈	196.22	1.18
1-Docosene	C ₂₂ H ₄₄	308.58	0.03				
3,7,11-Trimethyl-1-Eicosanol	C ₂₃ H ₅₁ O	343.55	0.01				
2-Undecene	C ₁₁ H ₂₂	154.29	2.75				
1-Hexyl-2-propyl cis-2-octene	C ₈ H ₁₆	122.21	0.72				
1-butyl-2-pentyl trans- cyclopropane	C ₁₂ H ₂₄	168.32	0.01				
5-Undecene	C ₁₁ H ₂₂	154.29	0.66				
1,12-Tridecadiene	C ₁₃ H ₂₄	180.33	0.10				
4-nonene	C ₉ H ₁₈	126.24	0.10				
9-oxabicyclo [6.1.0] nonane	C ₈ H ₁₄ O	126.20	0.11				
13-Octadecenal	C ₁₈ H ₃₄ O	266.46	0.34				
1-Tridecene	C ₁₃ H ₂₆	182.35	9.53				
n-Heptadecanol-1	C ₁₇ H ₃₆ O	256.47	0.54				
5-Tetradecene	C ₁₄ H ₂₈	196.38	0.29				
1-Tetradecene	C ₁₄ H ₂₈	196.38	8.85				
2-Tetradecene	C ₁₄ H ₂₈	196.38	3.11				
Cyclohexadecane	C ₁₆ H ₃₂	224.43	0.07				
n-pentadecanol	C ₁₅ H ₃₂ O	228.42	0.01				
8-heptadecene	C ₁₇ H ₃₄	238.27	0.01				
Dodecyl propyl ester Oxalic acid	C ₁₇ H ₃₂ O ₃₄	300.43	0.58				

TABLE 6

HYDROCARBON COMPOSITION OF FUEL DISTILLATES BY Al₂O₃

Compound Name	Compound Formula	Molecular Weight	%
Cis-2-nonene	C ₉ H ₁₈	126.24	0.16
4-Nonene	C ₉ H ₁₈	126.24	0.07
Cyclopropane, 1-methyl-2- pentyl-	C ₉ H ₁₈	126.24	2.35
(Z)-5- Decene	C ₁₀ H ₂₀	140.27	0.66
4-Decene	C ₁₀ H ₂₀	140.27	0.30
2-Decene	C ₁₀ H ₂₀	140.27	0.19
Cis-3-decene	C ₁₀ H ₂₀	140.27	4.10
2,7-Octadiene	C ₈ H ₁₄	110.20	0.30
4-Undecene	C ₁₁ H ₂₂	154.29	0.71
(E)-7-oxabicyclo [4.1.0] hep- tane, 3 methyl-	C ₇ H ₁₂ O	112.17	1.14
5-Undecene	C ₁₁ H ₂₂	154.29	0.36
2-Undecene	C ₁₁ H ₂₂	154.29	5.29
1-Hexadecanol	C ₁₆ H ₃₄ O	242.44	0.53
2-Dodecene	C ₁₂ H ₂₄	168.32	1.78
3,7,11-trimethyl -1-Dodecanol	C ₁₅ H ₃₂ O	228.41	1.16
2-butyl-Dodecane	C ₁₆ H ₃₄	226.44	5.25
5-Octadecene	C ₁₈ H ₃₆	252.48	1.02
Trichloroacetic acid, undecyl ester	C ₁₃ H ₂₃ Cl ₃ O ₂	317.68	2.54
Cis-4-Undecene	C ₁₁ H ₂₂	154.29	0.96
Tridecene	C ₁₃ H ₂₈	184.22	5.71
3-Tetradecene	C ₁₄ H ₂₈	196.38	1.57
5-Tetradecene	C ₁₄ H ₂₈	196.38	0.64
Oxalic acid	C ₂ H ₂ O ₄	90.03	3.74

TABLE 7

HYDROCARBON COMPOSITION OF FUEL DISTILLATES BY ZnO

Compound Name	Compound Formula	Molecular Weight	%
3-Nonen-2-ol	C ₉ H ₁₈ O	142.24	0.26
2-Nonene	C ₉ H ₁₈	126.24	2.41
4-Nonene	C ₉ H ₁₈	126.24	0.21
Trans-4-Nonene	C ₉ H ₁₈	126.24	1.91
Cyclohexane, 1,3-dimethyl-2- methylene	C ₉ H ₁₆	124.22	0.31
6-Tridecene	C ₁₃ H ₂₈	184.22	0.51
E-2-Octadecadecen-1-ol	C ₁₈ H ₃₆ O	268.48	0.57
Decane	C ₁₀ H ₂₂	142.28	5.04
Cis-4-Decene	C ₁₀ H ₂₀	140.27	1.77
(E)-Trans-4-Decene	C ₁₀ H ₂₀	140.27	1.97
3, 4-Octadiene	C ₈ H ₁₄	110.20	0.55
9-Methylbicyclo[3.3.1] non- ane	C ₁₀ H ₁₈	138.25	1.11
Undecane	C ₁₁ H ₂₄	156.31	6.43
(Z)-4-Undecene	C ₁₁ H ₂₂	154.29	0.97
Dodecane	C ₁₂ H ₂₆	170.33	5.53
(Z)-5-Dodecene	C ₁₂ H ₂₄	168.32	0.74
8-Dodecen-1-ol, (Z)-	C ₁₂ H ₂₄ O	184.32	0.13
Tridecene	C ₁₃ H ₂₈	184.22	5.39
2-Tetradecene	C ₁₄ H ₂₈	196.38	4.38
Z-5-Nonadecene	C ₁₉ H ₃₈	266.51	1.48
1-Nonadecene	C ₁₉ H ₃₈	266.51	0.01
(Z)-Oxirane	C ₂ H ₄ O	44.05	0.04
Oxalic acid	C ₂ H ₂ O ₄	90.03	0.10
(Z)-2-Tridecene	C ₁₃ H ₂₆	182.35	0.24
1-Tridecene	C ₁₃ H ₂₆	182.35	0.09
1-Dodecene	C ₁₂ H ₂₄	168.32	0.09
2,5-dimethyl dodecane	C ₁₄ H ₃₀	198.39	4.97
1,9Tetradecadiene	C ₁₄ H ₂₆	194.36	0.14
1-Eicosanol	C ₂₀ H ₄₂ O	298.55	7.77
13-Octadecenal	C ₁₈ H ₃₄ O	266.46	0.57
7-Hexadecene	C ₁₆ H ₃₂	224.43	3.85
(Z)-Cyclohexadecane	C ₁₆ H ₃₂	224.43	0.25
3-Hexadecene	C ₁₆ H ₃₂	224.43	0.14
Cyclotetradecane	C ₁₄ H ₂₈	196.37	2.84
Octadecane	C ₁₈ H ₃₈	254.49	0.01
Heptadecanoic acid	C ₁₇ H ₃₄ O ₂	270.45	0.01

Other studies employed the use of a batch reactor which converted a mixture of LDPE, HDPE, PVC and PP into light hydrocarbons at low temperature [2], [15], [16], [17]. The use of Fluidized Catalytic Cracking (FCC) units in converting LDPE to fuel as well as improving the quality and yield of conventional petroleum products has also been reported [13], [18], [19]. Chemical processes that make use of fluidized bed reactors and zeolite-based catalysts which were operated iso-

thermally and at ambient pressure have also been able to produce liquid and volatile hydrocarbons [9], [19]. It is expected that the design of various techniques to improve the conversion process which includes lowering reaction temperature and finding optimum polymer vs. catalyst ratios for various catalysts, including calcium hydroxide. The reaction kinetics is another factor that influences the conversion yield.

4 CONCLUSION

The current study tested the hypothesis of whether or not LDPE can be converted to gasoline fuel type via $\text{Ca}(\text{OH})_2$, Al_2O_3 and ZnO catalysis. The results show that $\text{Ca}(\text{OH})_2$ proved to be the best catalyst, followed by Al_2O_3 and then ZnO [$\text{Ca}(\text{OH})_2 > \text{Al}_2\text{O}_3 > \text{ZnO}$]. That is, $\text{Ca}(\text{OH})_2$ gave the highest yield (100%) and liquid conversion (79.8%). In addition, the 1:4 catalyst-to-polymer ratio proved to be the optimum ratio for the synthesis of liquid fuel using any of the catalysts applied in the current study. Study of catalyst regeneration is currently underway in order to fully ascertain the possibility of using $\text{Ca}(\text{OH})_2$ on an industrial scale.

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REFERENCES

- [1] Plastics Europe, "Plastics—The Facts (2012): An Analysis of European Plastics Production, Demand and Waste Data for 2011," <http://www.plasticseurope.org/Document/plastics-the-facts-2012-9894.aspx>, 2012.
- [2] M. Sarker, M.M. Rashid, and M.S. Rahman, "Low Density Polyethylene (LDPE) Waste Plastic Transformation into Renewable Heavy Fuel Using Thermal Cracking," *World Environment*, vol. 2, pp. 140-147, 2012.
- [3] M. Sarker, "Municipal Waste Plastic Conversion into Different Category Liquid Hydrocarbon Fuel," *Chemistry, Emission Control, Radioactive Pollution and Indoor Air Quality*, N. Mazzeo, ed., InTech, available at <http://www.intechopen.com/books/chemistry-emission-control-radioactive-pollution-and-indoor-air-quality/municipal-waste-plastic-conversion-into-different-category-liquidhydrocarbon-fuel>, 2011.
- [4] C. Osueke and I. Ofondu, "Conversion of Waste Plastics (Polyethylene) to Fuel by Means of Pyrolysis," *Int. J. of Advanced Engineering Sciences and Technologies*, vol. 4, pp. 021 – 024, 2011.
- [5] M.R. Jan, J. Shah, and H. Gulab, "Catalytic Degradation of High-density Polyethylene into Fuel Products using BaCO_3 as a Catalyst," *Fuel Processing Technology*, vol. 91, no. 11, pp. 1428 –1437, 2010.
- [6] M. Sarker and M.M. Rashid, "Catalytic Conversion of Low Density Polyethylene and Polyvinyl Chloride Mixture into Fuel Using Al_2O_3 ," *Int. J. of Materials, Methods and Technologies*, vol. 1, no. 2, pp. 8-16, 2013.
- [7] N. Patni, P. Shah, A. Shruti, and P. Singhal, "Alternative Strategies for Conversion of Waste Plastic to Fuels," *ISRN Renewable Energy*, vol. 2013, pp. 1-7, 2013.
- [8] Q. Zhou, Y.-Z. Wang, C. Tang, and Y.-H. Zhang, "Modifications of ZSM-5 Zeolites and their Applications in Catalytic Degradation of LDPE," *Polymer Degradation and Stability*, vol. 80, no. 1, pp. 23-30, 2003.
- [9] 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, no. 9., pp. 2305-2316, 2010.
- [10] D.C. Tiwari, A. Ejaz, and K. Singh, "Catalytic Degradation of Waste Plastic to Fuel Range Hydrocarbons," *Int. J. of Chemical Research*, vol. 1, no. 2, pp. 31-36, 2009.
- [11] H.S. Shah, M.Z. Khan, A.I. Raja, Q. Mahmood, A.Z. Bhatti, J. Khan, A. Farooq, N. Rashid, and D. Wu, "Low Temperature Conversion of Plastic Waste into Light Hydrocarbons," *J. of Hazardous Materials*, vol. 179, nos. 1-3, pp. 15–20, Jul. 2010.
- [12] J. Shah, M.R. Jan, and Z. Hussain, "Catalytic Pyrolysis of Low Density Polyethylene with Lead Sulphide into Fuel Oil," *Polymer Degradation and Stability*, vol. 87, no. 2, pp. 329-333, Feb. 2005.
- [13] F.J. Passamonti and S. Ulises, "Recycling of Waste Plastics into Fuels: LDPE Conversion in FCC," *Applied Catalysis B: Environmental*, vol. 125, pp. 499-506, Aug. 2012.
- [14] 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 Perspective," *Renewable and Sustainable Energy Reviews*, vol. 14, no. 1 pp. 233-248, 2010.
- [15] M. Sarker, M.M. Rashid, M.S. Rahman, and M. Molla, "Fractional Distillation Process Utilized to Produce Light Fractional Fuel from Low Density Polyethylene (LDPE) Waste Plastic," *The Open Fuels & Energy Science Journal*, vol. 5, pp. 39-46, Jan. 2012.
- [16] M. Sarker and M.M. Rashid, "Mixture of Waste Plastics to Fuel Production Process Using Catalyst Percentage Ratio Effect Study," *Int. J. of Environmental Engineering Science and Technology Research*, vol. 1, pp. 1-19, 2013.
- [17] M. Sarker, M.M. Rashid, M.S. Rahman, and M. Molla, "Environmentally Harmful Low Density Waste Plastic Conversion into Kerosene Grade Fuel," *J. of Environmental Protection*, vol. 3, no. 8, pp. 700-708, Aug. 2012.
- [18] G. De la Puente, C. Klocker, and U. Sedran, "Conversion of Waste Plastics into Fuels: Recycling Polyethylene in FCC," *Applied Catalysis B: Environmental*, vol. 36, no. 4, pp. 279-285, Mar. 2002.
- [19] M. Sarker, M.M. Rashid, and M. Molla, "Liquid Hydrocarbon Fuel Conversion from Abundant Solid Waste Low Density Polyethylene (LDPE-4) Plastics," *Int. Rev. of Chemical Engineering*, vol. 3, no. 3, pp. 340-349, May 2011.