

# Portland Cement – Catalyzed Pyrolysis of Waste Polypropylene for Production of Liquid Fuel Comparable to Commercial Grade Diesel

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**Abstract**—In the present study, a Portland cement (PC) was used for the first time as very cheap and commercially available catalyst for the low-temperature pyrolysis of waste polypropylene (WPP) to a liquid fuel comparable to the commercial grade diesel, utilizing a single-stage semi-batch reactor designed well at appropriate pyrolyzer / catalytic reformer ratio. The thermal decomposition of WPP was studied using a thermogravimetric analysis (TGA). The liquid fuel produced by catalytic pyrolysis of WPP at 280 °C was investigated by means of gas chromatography – mass spectrometry (GC–MS), Infrared (IR) spectroscopy, and physico-chemical properties of fuels. The PC-catalyzed pyrolysis resulted in remarkably increased liquid and gaseous products, and reduced char yield. Moreover, it significantly prevented the wax production.

**Index Terms**— Catalytic pyrolysis, Liquid fuel, WPP, PC, IR, CG–MS.

## 1 INTRODUCTION

OWING to the various advantages of plastics, such as their low price, easy machining, smooth processing surface, excellent hardness, and high strength, their consumption has largely been increased in recent decades. This has led in parallel to growing waste plastics disposed in landfills causing a serious danger towards the environment due to their slow degradation and subsequent contaminants generation. In other hand, the incineration of waste plastics emits severe air pollutants which also lead to environmental hazards [1–3]. Therefore. Many methods for recovering and recycling waste plastics have been developed. Among these with a view of the environmental protection and reduction of non-generation resources, a pyrolysis have attracted a crucible interest worldwide [4–6]. The pyrolysis is a thermal conversion method widely applied to waste plastics for the production of liquid fuel, which can be used as a fuel or chemical feedstock.

However, the conventional thermal pyrolysis suffers from certain limitations, such as high temperatures required [7], very broad product range with low yield % of produced liquid and gas fuels [8], and difficult decomposition of crossed chain polymers, e.g., high-density, and low-density polyethylene (HDPE and LDPE) with polypropylene (PP) [9]. The catalytic pyrolysis has been developed to overcome such problems. Moreover, the use of catalyst can reduce the pyrolysis temperature, and also enhance the quality of the pyrolytic products in terms of desired range of carbon atom number and high energy efficiency [10–12].

Because of their simple design and easy operation, batch / semi-batch reactors have been used widely for the catalytic pyrolysis of plastics. But the *in situ* catalytic pyrolysis, in which the catalysts and plastic feedstock are in direct contact with each other in a single-stage batch reactor, has many drawbacks, such as low reaction rates, fast catalyst deactivation [12], and sophisticated catalyst recovery [13]. Such problems can however be resolved via *ex situ* catalytic pyrolysis by designing semi-batch reactors with a combination of sequential pyrolysis and catalytic reforming stages [14–19].

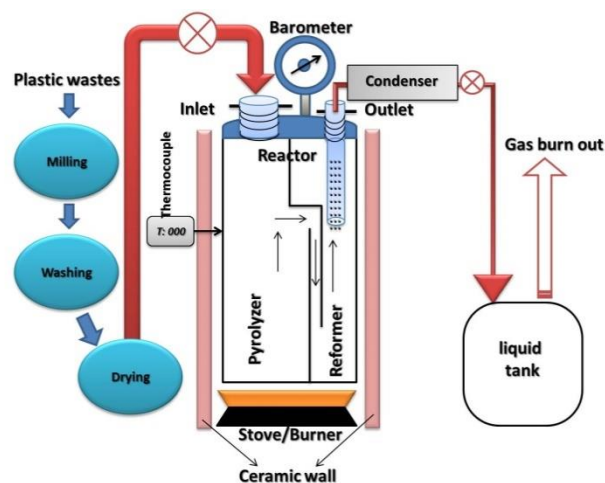


Fig. 1. Schematic of process and semi-batch reactor used for the catalytic pyrolysis.

The war and conflicts going on in Yemen since the past five years have led to increasing prices of fuels by nearly ten orders of magnitude, e.g., the diesel fuel, as well as the uncontrollable accumulation of garbage and waste plastics within the main streets of cities, particularly Taiz city which is still being

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blockaded till now. This has given us a motivation to conduct our research project on the catalytic pyrolysis of waste plastics for achieving that two-fold objective. In the present work, a Portland cement (PC) was used for the first time as very cheap and available catalyst for producing diesel range pyrolytic oil by the catalytic pyrolysis of waste polypropylene (WPP) as one of the most abundant waste plastics in Yemen, and has a large number of hydrocarbon groups, which are linearly chained. A single-stage semi-batch reactor made of stainless steel was designed in a cylindrical geometry with the overall capacity of 0.20 m<sup>3</sup>, so that pyrolyzer to catalytic reforming portion was maintained at the ratio of 3:1 (Fig. 1).

## 2 MATERIALS & METHODS

The catalyst used was a high-quality Portland cement (PC), purchased from the local market supplied by the National Cement Company (NCC) – Hayel Saeed Anam & Co Ltd. (HAS), Lahij – Yemen. Finely ground powder of the PC catalyst was activated by pre-heating at 500 °C in a muffle furnace for 5 hrs.

Samples of WPP were collected from garbage sites and landfills located in several regions of Taiz city, Yemen. The WPP samples were milled into small pieces of 1.5 – 2 cm size and thoroughly mixed. The resultant WPP pieces were washed using liquid detergent and water to remove any dirt or oils, and then dried under sun light.

The catalytic pyrolysis experiments were carried out in a single-stage semi-batch reactor made of stainless steel as shown in Fig. 1 by packing the as-dried WPP pieces into the pyrolyzer upto the two thirds of its capacity. The activated PC catalyst (9 % with respect to the total WPP added) was then introduced to cover the bottom of catalytic reformer. The nitrogen gas was pumped into the tightly closed reactor for 15 min to displace the resident air prior to the pyrolysis. The reactor was thereafter heated gradually at a constant heating rate of 15 °C min<sup>-1</sup>. The pyrolytic liquid products were allowed to condensate out into a stainless steel container at fixed outlet temperature and pressure 280 °C and 2.5 bar, respectively maintained over whole the pyrolysis process. The gas products were burned out in air at the vent of the container to avoid the emission of hydrocarbon gases into the atmospheric environment. The yield % of each pyrolytic product (*i.e.*, char, liquid, gas, and wax) was calculated after the completion of production based on the standard mass balance.

The thermal decomposition of WPP was investigated by means of simultaneous thermogravimetric– differential thermal (TG–DT) analysis using a Perkin Elmer thermal analyzer. A 15– mg dried WPP powder sample was applied against  $\alpha$ -alumina as a reference material. The instrument was run with 10 °C min<sup>-1</sup> heating rate and flowing a nitrogen gas from ambient temperature of 40 °C to 600 °C, and then air flowing upto 850 °C at a constant flow rate of 100 mL min<sup>-1</sup>.

The chemical composition of pyrolyzed liquid fuel was investigated by the gas chromatography coupled with mass spectrometry (GC–MS) using a Shimadzu–QP–2010 Ultra instru-

ment with a flame ionization (FI) detector. An 1.0  $\mu$ L liquid sample was injected by a split mode into a HP–PONA capillary column (50 m  $\times$  0.25 mm i.d., 0.50  $\mu$ L thick). Helium of high purity was used as a carrier gas with a purge flow rate of 5 mL min<sup>-1</sup>. The oven temperature was first set at 40 °C for 1 min, and it was thereafter increased upto 150 °C with a heating rate of 2 °C min<sup>-1</sup>. The temperature of the ion source and interface were maintained at 200, and 250 °C, respectively. The chromatographic peaks were identified by means of the NIST mass spectral data library.

A Shimadzu IR spectrometer was also used to identify the functional groups of compounds present in the produced liquid fuel. IR spectrum was scanned within the frequency range of 4000 – 400 cm<sup>-1</sup> with a spectral resolution of 4 cm<sup>-1</sup>.

The high heating value, flash point, kinematic viscosity, and some other properties of liquid fuel were measured according to standard ASTM methods, considering three replications each.

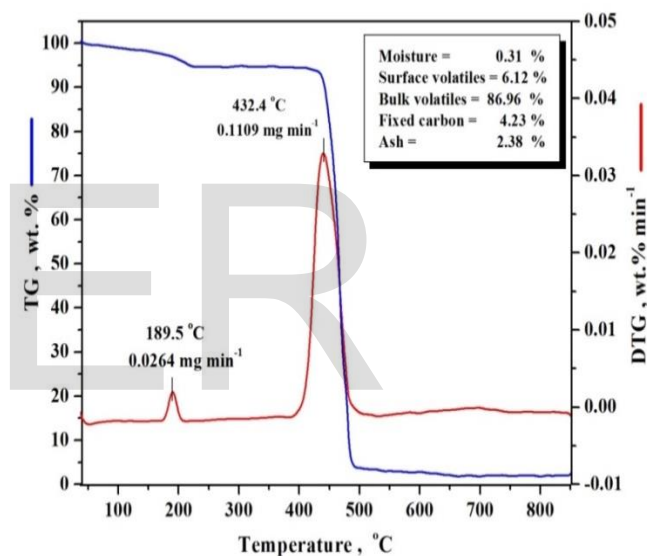


Fig. 2. TG and DTG curves of WPP.

## 3 RESULTS & DISCUSSION

Fig. 2 shows TG and DTG curves of WPP. A clear two-step thermal degradation is observed in the nitrogen atmosphere, *i.e.* in the temperature range of 40 – 600 °C, where the instrument was run under nitrogen flowing. The very low weight loss of the first step as 189.5 °C may be attributed to the elimination of short, defective PP chains, which weakly bound to the surfaces of WPP particles. While the second high loss occurring at 432.4 °C is evidently the characteristic feature of the thermal history of the single step degradation of virgin PP [20]. Thus, the weight loss % of the first and second step were referred to the surface and bulk volatiles, respectively. The proximate analysis of WPP degradation is illustrated in the inset of Fig. 2. The moisture content was calculated from the weight loss % between ambient temperature and 150 °C. The ash content was equal to a constant weight % remaining after

heating the sample at temperatures greater than 600 °C under air flowing. The fixed carbon was then computed using the mass % balance equation. It is interesting to note that the ash content and total volatiles play an important role in the production of liquid fuels by pyrolysis of waste plastics. The higher the ash content, the higher the production of gases and char, and the increase of volatile materials enhances the liquid yields.

The effect of the presence of PC- catalyst on the distribution of the product yields for WPP pyrolysis at 280 °C can be seen in Fig. 3. As expected, the PC- catalyzed pyrolysis resulted in remarkably increased liquid and gaseous products coupled with the reduction of char yield as compared to the uncatalyzed pyrolysis. Interestingly, the PC- catalysis prevents the production of wax. These results are well agreed with what have been reported for the catalytic pyrolysis of some waste plastics [9,21–23].

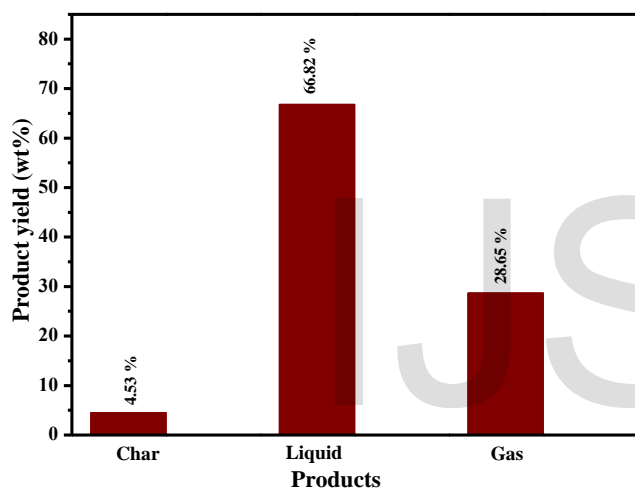


Fig. 3. Distribution of product yields of PC- catalyzed pyrolysis of WPP.

The GC–MS results of liquid fuel produced by the catalytic pyrolysis of WPP is illustrated in Fig. 4, and Tables 1. The last two hydrocarbons eluted at retention time (RT) of 46.14, and 48.02 min for the liquid fuel produced by the PC- catalyzed pyrolysis are heptacosane (C<sub>27</sub>H<sub>56</sub>), and 2,5,10,15- tetramethylheptadecane (C<sub>21</sub>H<sub>44</sub>) (Table 1).

The IR spectroscopy can also be used as a powerful characterization technique for identifying the chemical functional groups present in the pyrolyzed liquid fuels [4,24,25].

The IR spectrum of liquid fuel obtained from the functional groups in the investigated fuel is shown in Fig.5. The broad band in the region 3500 – 3200 cm<sup>-1</sup> accounts for the O–H stretching of alcohols and water residue. The two joint peaks at ~ 2920 and 2870 cm<sup>-1</sup> are assigned to stretching vibrations of C–CH<sub>3</sub> and –CH<sub>2</sub>–, respectively. The strong wide band in the region 1700 – 1610 cm<sup>-1</sup> can be ascribed to the presence of C=O groups, while the shoulder apparent at ~ 1560 cm<sup>-1</sup> is due to the aliphatic C=C stretching vibrations.

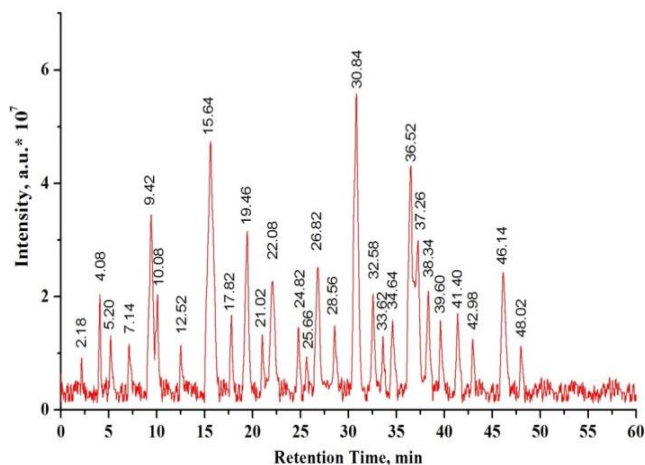


Fig. 4. GC-MS chromatograms of liquid fuels produced by PC- catalyzed pyrolysis of WPP.

Although the GC–MS analysis showed on any carbonyl compound, the presence of C=O group in the liquid fuel under investigation as assigned by its IR spectra without a doubt arises from the pyrolyzed enols (Tables 1), which undergo a reversible tautomerization to carbonyl compounds [26]. The scissor vibrations of –CH<sub>2</sub>– and antisymmetric deformation of –CH<sub>3</sub> can be seen in the range of 1480 – 1400 cm<sup>-1</sup>. The short band at ~ 1230 cm<sup>-1</sup> is assigned to the C≡C stretching vibrations and the two peaks at ~ 1100 and 1030 cm<sup>-1</sup> may be attributed to the different alcoholic and carbonyl C–O stretching vibrations. However, the three peaks at ~ 950, 880 and 815 cm<sup>-1</sup> are a clear evidence for the presence of (*cis*) –CH=CH– and conjugated polyenes.

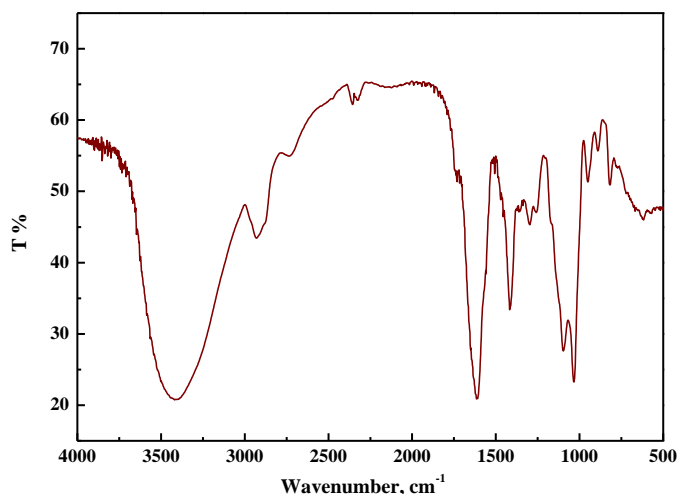


Fig. 5. IR spectrum of liquid fuel produced by PC- catalyzed pyrolysis of WPP.

Based on the GC–MS results of the liquid fuel produced by PC- catalyzed pyrolysis of WPP, the distribution of pyrolyzed

TABLE 1  
LIST OF GC-MS IDENTIFIED COMPOUNDS PRESENT IN THE LIQUID FUEL OBTAINED FROM PC- CATALYZED PYROLYSIS OF WPP.

| Peak # | RT (min) | Peak area % | Trace Mass (m/z) | Name                                | Formula                           | MW  | Prob% | NIST Lib # |
|--------|----------|-------------|------------------|-------------------------------------|-----------------------------------|-----|-------|------------|
| 1      | 2.18     | 0.77        | 81               | Cyclohexene, 4-methyl-              | C <sub>7</sub> H <sub>12</sub>    | 96  | 14.3  | 125422     |
| 2      | 4.08     | 3.09        | 91               | 1,3,5-Cycloheptatriene              | C <sub>7</sub> H <sub>8</sub>     | 92  | 18.1  | 230230     |
| 3      | 5.20     | 1.09        | 55               | 2-Octene, (E)-                      | C <sub>8</sub> H <sub>16</sub>    | 112 | 23.6  | 107269     |
| 4      | 7.14     | 1.32        | 81               | Bicyclo[4.1.0]heptane, 3-methyl-    | C <sub>8</sub> H <sub>14</sub>    | 110 | 11.5  | 46298      |
| 5      | 9.42     | 6.20        | 67               | Cyclopentane, (1-methylethylidene)- | C <sub>8</sub> H <sub>14</sub>    | 110 | 14.9  | 61656      |
| 6      | 10.08    | 3.34        | 83               | Cyclohexane, ethyl-                 | C <sub>8</sub> H <sub>16</sub>    | 112 | 39.8  | 113476     |
| 7      | 12.52    | 1.31        | 43               | Cyclohexanol, 2,4-dimethyl          | C <sub>8</sub> H <sub>16</sub> O  | 128 | 10.6  | 114589     |
| 8      | 15.64    | 12.25       | 55               | 1-Undecene                          | C <sub>11</sub> H <sub>22</sub>   | 154 | 7.7   | 34717      |
| 9      | 17.82    | 1.32        | 57               | Decane                              | C <sub>10</sub> H <sub>22</sub>   | 142 | 41.4  | 291484     |
| 10     | 19.46    | 5.98        | 56               | 3-Undecene, (Z)-                    | C <sub>11</sub> H <sub>22</sub>   | 154 | 7.5   | 142598     |
| 11     | 21.02    | 1.08        | 55               | 1,11-Dodecadiene                    | C <sub>12</sub> H <sub>22</sub>   | 166 | 8.1   | 6213       |
| 12     | 22.08    | 3.32        | 41               | 1-Tridecene                         | C <sub>13</sub> H <sub>26</sub>   | 182 | 12.7  | 107768     |
| 13     | 24.82    | 1.16        | 55               | 1-Hexadecyne                        | C <sub>16</sub> H <sub>30</sub>   | 222 | 7.7   | 233098     |
| 14     | 25.66    | 0.81        | 55               | 4-Tetradecene, (E)-                 | C <sub>14</sub> H <sub>28</sub>   | 196 | 9.3   | 142625     |
| 15     | 26.82    | 4.04        | 55               | E-2-Hexadecacene-1-ol               | C <sub>16</sub> H <sub>32</sub> O | 240 | 10.6  | 131101     |
| 16     | 28.56    | 1.39        | 55               | 1-Hexadecene                        | C <sub>16</sub> H <sub>32</sub>   | 224 | 6.4   | 118882     |
| 17     | 30.84    | 16.23       | 57               | Octadecane                          | C <sub>18</sub> H <sub>36</sub>   | 254 | 18.9  | 57273      |
| 18     | 32.58    | 3.08        | 97               | E-2-Octadecadecene-1-ol             | C <sub>18</sub> H <sub>36</sub> O | 268 | 7.6   | 131102     |
| 19     | 33.62    | 1.08        | 55               | 9-Nonadecene                        | C <sub>19</sub> H <sub>38</sub>   | 266 | 10.2  | 113627     |
| 20     | 34.64    | 1.29        | 55               | 1-Nonadecene                        | C <sub>19</sub> H <sub>38</sub>   | 266 | 8.8   | 113626     |
| 21     | 36.52    | 11.41       | 57               | Eicosane                            | C <sub>20</sub> H <sub>42</sub>   | 282 | 17.6  | 290513     |
| 22     | 37.26    | 5.68        | 55               | 10-Heneicosene                      | C <sub>21</sub> H <sub>42</sub>   | 294 | 9.4   | 113073     |
| 23     | 38.34    | 3.56        | 57               | Heneicosane                         | C <sub>21</sub> H <sub>44</sub>   | 296 | 33.7  | 107569     |
| 24     | 39.60    | 1.24        | 57               | 1-Docosene                          | C <sub>22</sub> H <sub>44</sub>   | 308 | 8.7   | 113878     |
| 25     | 41.40    | 1.71        | 57               | 1-Tricosene                         | C <sub>23</sub> H <sub>47</sub>   | 323 | 5.3   | 133854     |
| 26     | 42.98    | 1.07        | 55               | E-2-Docosene                        | C <sub>22</sub> H <sub>44</sub>   | 308 | 6.7   | 113879     |
| 27     | 46.14    | 3.85        | 55               | Heptacosane                         | C <sub>27</sub> H <sub>56</sub>   | 380 | 7.4   | 150574     |
| 28     | 48.02    | 1.29        | 55               | Heptadecane,2,6,10,15-tetramethyl-  | C <sub>21</sub> H <sub>44</sub>   | 296 | 10.4  | 14103      |

compounds in terms of their chromatographic peak area % as a function of cyclization, carbon number range, and saturation can be viewed in Figs. 6, 7, and 8, respectively. It is clear that the PC- catalysis leads to increased open- chain structures (Fig. 6), and a remarkable lowering of unsaturated compounds (Fig. 7) in the produced liquid. The interesting point to be emphasized here is that more than 50 % of hydrocarbons produced by the catalytic pyrolysis have a carbon range of C<sub>18</sub>–C<sub>24</sub>, followed by a kerosene (C<sub>11</sub>–C<sub>17</sub>) as much as 30.03 % (Fig. 8). This indicates that, to a great extent, the liquid fuel pyrolyzed by the PC- catalysis approaches the composition of conventional diesel [27–29]. These results suggest that the PC- catalyzed pyrolysis of WPP follows the free – radical mechanism proposed by Sekine and Fujimoto for the pyrolysis of PP catalyzed with the Fe-activated carbon [30]. Values of characteristic parameters of liquid fuel obtained from the catalytic pyrolysis of WPP are summarized in Table 2. It can be observed that the properties measured for the produced liquid fuel of the PC- catalyzed pyrolysis significantly match well with the GC–MS results revealed earlier. Interestingly, These parameters measured for the pyrolyzed liquid fall within the acceptable ranges reported for the conventional

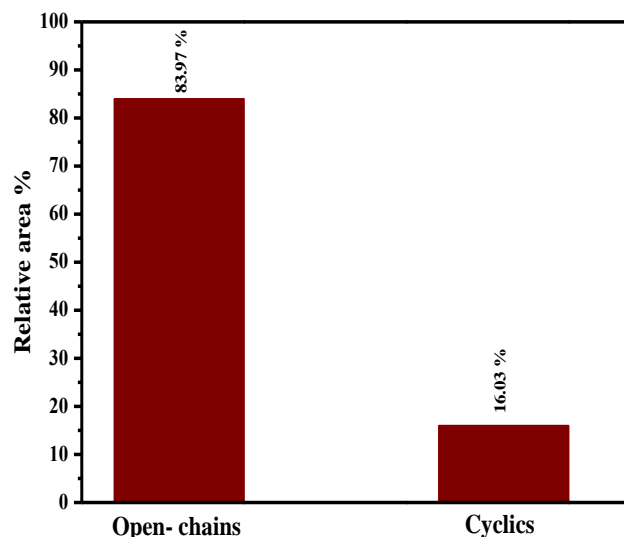


Fig. 6. Distribution of open- chain and cyclic compounds of liquid fuel produced by catalytic pyrolysis of WPP.

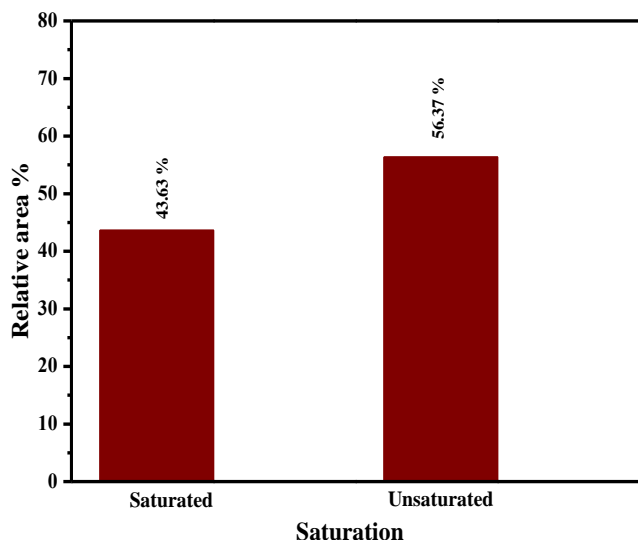


Fig. 7. Distribution of saturated and unsaturated compounds of liquid fuel produced by catalytic pyrolysis of WPP.

diesel [7,19,31]. Therefore, the results obtained in the present study prove that the low-temperature pyrolysis of WPP catalyzed with a low-cost Portland cement can potentially be used for producing high-yield liquid fuels comparable to the commercial grade diesel.

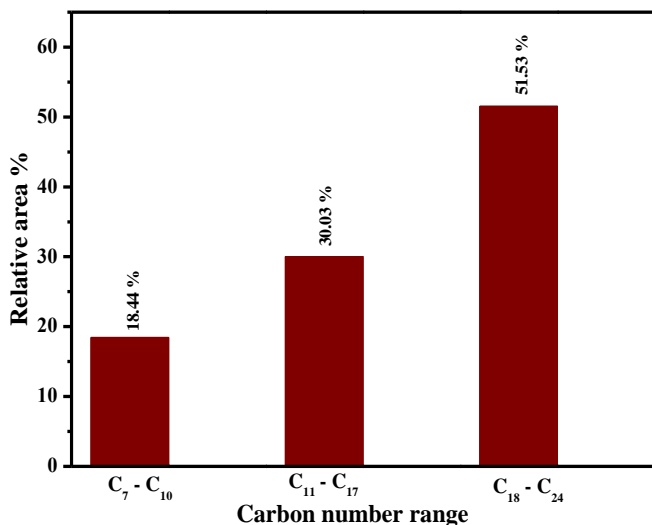


Fig. 8. Distribution of carbon number ranges for compounds of liquid fuel produced by catalytic pyrolysis of WPP.

TABLE 2  
PROPERTIES OF LIQUID FUEL PRODUCED BY PC- CATALYZED PYROLYSIS OF WPP.

| Properties                  | Unit              | Catalytic pyrolysis | Test method |
|-----------------------------|-------------------|---------------------|-------------|
| High heating value          | MJ/kg             | 44.79               | ASTM D 240  |
| Flash point                 | °C                | 29                  | ASTM D 93   |
| Fire point                  | °C                | 37                  | -           |
| Cetane index                | -                 | 44                  | ASTM D 976  |
| Carbon residue              | wt %              | 0.092               | ASTM D 189  |
| Moisture content            | wt %              | 0.086               | ASTM D 95   |
| Density @ 20 °C             | kg/m <sup>3</sup> | 802.7               | ASTM D1298  |
| Kinematic viscosity @ 40 °C | cSt               | 2.18                | ASTM D 445  |

#### 4 CONCLUSION

The use of very cheap and commercially available Portland cement along with the simple semi-batch reactor designed well at appropriate ratio of pyrolyzer and catalytic reformer feasibly allowed the low-temperature production of high-yield liquid fuel from the WPP pyrolysis. The hydrocarbon composition and functional properties of the liquid fuel produced by the PC-catalyzed pyrolysis were found to be similar to what have been reported for the commercial grade diesel. It can be concluded that the use of the produced liquid fuel as a substitute of , or blended with the conventional diesel, besides other products (gas and char) having a variety of promising applications, would essentially enhance the economic viability of the catalytic pyrolysis of waste plastics. Moreover, this will contribute to address the problems related to the environmental protection from the accumulation of such waste plastics.

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#### REFERENCES

- [1] Zhang X, Lei H. Synthesis of high-density jet fuel from plastics via catalytically integral processes. *RSC Advances* 2016;6:6154–6163.)
- [2] Adrados A, de Marco I, Caballero BM, López A, Laresgoiti MF, Torres A. Pyrolysis of plastic packaging waste: A comparison of plastic residuals from material recovery facilities with simulated plastic waste. *Waste Management* 2012;32:826–832.
- [3] Wong SL, Ngadi N, Abdullah TAT, Inuwa IM. Current state and future prospects of plastic waste as source of fuel: a review. *Renewable and Sustainable Energy Reviews* 2015;50:1167–1180.
- [4] Sarker M, Rashid MM. Polypropylene waste plastic conversion into fuel oil by using thermal degradation with fractional process. *American Journal of Environment, Energy and Power Research* 2014; 2:1–10.

- [5] Demirbas A. Pyrolysis of municipal plastic wastes for recovery of gasoline-range hydrocarbons. *Journal of Analytical and Applied Pyrolysis* 2004;72:97–102.
- [6] Faravelli T, Pincioli M, Pisano F, Bozzano G, Dente M, Ranzi E. Thermal degradation of polystyrene. *Journal of Analytical and Applied Pyrolysis* 2001;60:103–121.
- [7] Miandad R, Barakat MA, Aburiazaiza AS, Rehan M, Nizami AS. Catalytic pyrolysis of plastic waste: A Review. *Process Safety and Environment Protection* 2016;102:822–838.
- [8] Sadaf Y, Nizami AS, Batool SA, Chaudhary MN, Ouda OKM, Asam ZZ, Habib K, Rehan M, Demirbas A. Waste-to-energy and recycling value for developing integrated solid waste management plan in Lahore. *Energy Sources, Part B: Economics, Planning, and Policy* 2016;11:569–579.
- [9] Achilias DS, Roupakias C, Megalokonomos P, Lappas A, Antonakou EV. Chemical recycling of plastic wastes made from polyethylene (LDPE and HDPE) and polypropylene (PP). *Journal of Hazardous Materials* 2007;149:536–542.
- [10] Lopez A, Marco DI, Caballero BM, Laresgoiti MF, Adrados A, Torres A. Pyrolysis of municipal plastic waste II: Influence of raw material composition under catalytic conditions. *Waste Management* 2011;31:1973–1983.
- [11] Lopez A, Marco ID, Caballero BM, Laresgoiti MF, Adrados A, Aranzabal A. Catalytic pyrolysis of plastic wastes with two different types of catalytic: ZSM-5 zeolite and Red Mud. *Applied Catalyst B: Environmental* 2011;104:211–219.
- [12] Escola JM, Aguado J, Serrano DP, Briones L. Transportation fuel production by combination of LDPE thermal cracking and catalytic hydroreforming. *Waste Management* 2014;34:2176–2184.
- [13] Aguado J, Serrano DP, Miguel GS, Castro MC, Madrid S. Feedstock recycling of polyethylene in a two-step thermo-catalytic reaction system. *Journal of Analytical and Applied Pyrolysis* 2007; 79:415–423.
- [14] Bagri R, Williams PT. Catalytic pyrolysis of polyethylene. *Journal of Analytical and Applied Pyrolysis* 2002;63:29–41.
- [15] Williams PT Bagri R. Hydrocarbon gases and oils from the recycling of polystyrene waste by catalytic pyrolysis. *International Journal of Energy Research* 2004;28:31–44.
- [16] Wang JL, Wang LL. Catalytic pyrolysis of municipal plastic waste to fuel with nickel-loaded silica-alumina catalysts. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects* 2011;33:1940–1948.
- [17] Miguel GS, Serrano DP, Aguado J. Valorization of waste agricultural polyethylene film by sequential pyrolysis and catalytic reforming. *Industrial and Engineering Chemistry Research* 2009;48:8697–8703.
- [18] Iribarren D, Dufour J, Serrano DP. Preliminary assessment of plastic waste valorization via sequential pyrolysis and catalytic reforming. *Journal of Material Cycles and Waste Management* 2012;14:301–307.
- [19] Syamsiro M, Saptoadi H, Norsujianto T, Noviasri P, Cheng S, Alimuddin Z, Yoshikawa K. Fuel oil production from municipal plastic wastes in sequential pyrolysis and catalytic reforming reactors. *Energy Procedia* 2014;47:180 – 188.
- [20] Mofokeng JP, Luyt AS, Tábi T, Kovács J. Comparison of injection moulded, natural fibre-reinforced composites with PP and PLA as matrices. *Journal of Thermoplastic Composite Materials* 2011;25:927–948.
- [21] Murata K, Brebu M, Sakata Y. The effect of silica-alumina catalysts on degradation of polyolefins by a continuous flow reactor. *Journal of Analytical and Applied Pyrolysis* 2010;89:30–38.
- [22] Liu W, Hu C, Yang Y, Tong D, Li G, Zhu L. Influence of ZSM-5 zeolite on the pyrolytic intermediates from the co-pyrolysis of polybutene and LDPE. *Energy Conversion and Management* 2010;51:1025–1032.
- [23] White RL. Acid-catalyzed cracking of polyolefins: primary reaction mechanism. In Scheirs J, Kaminsky W. (Eds.). *Feedstock recycling and pyrolysis of waste plastics* (pp. 45–72). Hoboken: John Wiley & Sons, 2006.
- [24] Kumar U, Gaikwad V, Mayyas M, Bucknall M, Sahajwalla V. Application of high-resolution NMR and GC-MS to study hydrocarbon oils derived from noncatalytic thermal transformation of e-waste plastics. *ACS Omega* 2018;3:9282–9289.
- [25] Hall WJ, Williams PT. Fast pyrolysis of halogenated plastics recovered from waste computers. *Energy and Fuels* 2006;20:1536–1549.
- [26] Cederstav AK, Novak BM. Investigations into the chemistry of thermodynamically unstable species: The direct polymerization of vinyl alcohol, the enolic tautomer of acetaldehyde. *Journal of the American Chemical Society* 1994;116:4073–4074.
- [27] Krkošová Ž, Kubinec R, Addová G, Jurdáková H, Blaško J, Ostrovský I, Soják L. Gas chromatographic-mass spectrometric characterization of monomethylalkanes from fuel diesel. *Petroleum and Coal* 2007;49:51–62.
- [28] Istoto EH, Widayat, Saptadi S. Production of fuels from HDPE and LDPE plastic waste via pyrolysis methods. *ICENIS 2019, E3S Web of Conferences* 2019;125, 14 011:1–4.
- [29] Zadora G, Borusiewicz R, Zięba-Palus J. Differentiation between weathered kerosene and diesel fuel using automatic thermal desorption-GCMS analysis and the likelihood ratio approach. *Journal of Separation Science* 2005;28:1467–1475.
- [30] Sekine Y, Fujimoto K. Catalytic degradation of PP with an Fe/activated carbon catalyst. *Journal of Material Cycles and Waste Management* 2003;5:107–112.
- [31] Yasin G, Bhangar MI, Ansari TM, Muhammad S, Naqvi SR, Talpur FN. Quality of commercial high speed diesel and its environmental impact. *Journal of Petroleum Technology and Alternative Fuels* 2012;3:29–35.