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RESEARCH PAPER

Conversion of waste polypropylene disposable cups into liquid fuels by thermal and catalytic pyrolysis using activated carbon

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Abstract. Polypropylene plastics are used extensively in packaging and food services for short usage, poseing enormous disposal problem and contributing to over 45% of globally generated plastic waste. Accordingly, the present work is focused on converting waste polypropylene (WPP) disposable cups into liquid fuels by employing thermal and catalytic pyrolysis processes. Characterization of WPP disposable cups were performed through proximate and ultimate analyses followed by TGA and found that 86% of its mass degrades in a temperature range of 430–603°C. An effect of temperature in the range of 500–650°C on liquid fuel production at a constant heating rate of 15°C /min noted in thermal pyrolysis, an optimum and stable liquid fraction of 76% with a reaction time of 30 min was recorded at 500°C. For studies on catalytic pyrolysis, activated carbon (AC) was applied from 470 to 530°C at variable Feed to Catalyst (F/C) ratio of 1- 4. An optimum liquid yield of 74% was obtained with a residence time of 35 min at 510°C and F/C of 3 :1. Thermo-physical properties of optimal liquid products were comparable with conventional fossil fuels. XRD and SEM analysis of AC catalyst showed the presence of carbon at 24° and 42° of 2θ-angle with an apparel pore size of 2 μm.

Keywords: thermal and catalytic pyrolysis; waste polypropylene; disposable cups; liquid fuels; activated carbon; energy recovery from waste plastics

1. Introduction

Plastic utilization has become indispensable part of human life due to their superior attributes which include excel durability, suppleness in design and light weight. By 2015, the world had produced 7.8 billion tonnes of plastic cumulatively from 1950; more than one tonne of plastic for every person alive (Geyer et al., 2017). According to estimations in 2015, around 3.11 billion tonnes of waste plastics were generated worldwide and packing sector alone has generated 1.41 billion tonnes of plastic waste. Packaging was the dominant use of primary plastics, with 42% entering into the phase of use with a very short 'in-use' lifetime and eventually dominates municipal plastic waste and subsequently turns into mismanaged waste (Geyer et al., 2017). The handful of resins that dominate the packaging and food service applications are also the most frequently found in municipal solid waste as well as in marine debris: these are polyethylene, polypropylene, polyethylene terephthalate and polystyrene. Generally, plastics in the global

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ecosystem is distributed into three major fractions: plastics in use, post-consumer managed plastic waste, and a mismanaged plastic waste (MPW), the last of which includes the urban litter (Omnexus, n.d.). The East Asia and Pacific region dominates global mismanaged plastic waste, accounting for 60 percent of the world total and followed South Asia region accounting for 11 %, largely driven by India (Jambeck et al., 2015). Approximately 80% of ocean plastics came from land through rivers or streams, and with the remainder originating from marine sources. For instance, Ganges River in India carried 0.12 million tonnes annually, the second largest amount carried by a river (Lebreton et al., 2017).

Polypropylene (PP) is a tough, rigid, crystalline and recyclable thermoplastic polymer, globally the second most abundant plastic material, behind polyethylene (PE), and widely used in a variety of applications because of properties such as high resistance to chemicals, relatively high melting point, high tensile strength, and corrosion resistance (Omnexus, n.d.; Parku et al., 2020). The global polypropylene market size was valued at 115.9 billion in 2019 and is projected to grow at a CAGR of 3.1% from 2020 to 2027 (Research and Market, 2020). For instance, the demand for Polypropylene (PP) in India grew at a CAGR of around 8.51% during 2015-2019 and is expected to achieve a healthy growth rate during the 2020 (Research and Market, 2020). It has also been identified as one of the most abundant fractions of plastic wastes ending up at landfills (Miskolczi et al., 2004; Onu et al., 1999; Sharuddin et al., 2017; Zhao et al., 2020)

Mechanical recycling, feedstock recycling for chemical or energy recovery, material recycling, biological recycling and landfilling are several types of approaches used for waste plastic management (Al-Salem et al., 2010). Increased landfilling without adequate feedstock or energy recovery, on which many developing countries rely, has also been associated with major health and environmental concerns, including ground water contamination, increased greenhouse gases (GHGs) emissions, risk of fire and explosion, human health hazard and sanitary problems (Kumar & Sharma, 2014).

Prior to 1980, there were no significant recycling methods and hence 100 percent of global plastic waste was just discarded into the environment. Plastic waste management by incineration and recycling has made significant progress during the past few decades. An estimated 55% of global plastic waste was landfilled, 25% was incinerated and 20% was recycled in 2015 and it was anticipated that the incineration and recycling rates would increase to 50% and 44% respectively by 2050 to reduce the landfilling of discarded waste plastics to 6% (Ritchie & Roser, 2018). Though the mechanical recycling of waste plastics has been reflected as an ecofriendly process, contaminants in recovered plastics pose substantial problems to solve due to the technical limitations of separation technology (Al-Salem et al., 2010). Higher caloric values of plastics match with conventional fuels, attracting them to be used as throughput material into incinerators to produce electric power, steam, and heat, though they are typically criticised for the high demand of energy and utilities associated with their operations.

However, given that plastics are derived from crude oil with an average gross energy required to produce 1 kg of polypropylene is 73 MJ (Boustead, 2005), they can be converted to their constituting chemicals such as petroleum refining cuts and petrochemicals via thermal and catalytic means of chemical or feedstock recycling treatment. Many approaches have been suggested and practiced by the present generation for socioeconomic energy conversion technologies for the production of liquid fuels from plastic waste feedstocks. Worldwide, petroleum and other liquid fuels are the dominant source of transportation energy although their share of transportation energy decline over IEO (2016) projected period from 96% in 2012 to 88% in 2040. The International Energy Outlook (IEO) 2016, explained that the energy consumption increases in the transportation sector at an annual average rate of 1.4%, from 104 quadrillion British thermal unit (BTU) in 2012 to 155 quadrillion Btu in 2040. It was also projected that the total transportation energy consumption in India shows substantial growth from 3.3

quadrillion Btu in 2012 to 10.9 quadrillion Btu in 2040, at an average annual increase of 4.4 % (IEO, 2016).

Advanced thermo-chemical treatment (TCT) methods namely pyrolysis has received renewed attention recently due to the numerous operational and environmental advantages it provides, given the global energy demand and unstable fuel market. Pyrolysis is defined as the process where thermal degradation in inert atmospheres of long chain organic materials occurs with the presence of a catalyst (catalytic pyrolysis) or without (thermal process). The long chains of the organic materials treated result in smaller and less complex ones by controlling the heat flow and pressure of the operation (Qinglan et al., 2014). Although pyrolysis is not an economic system for monomer recovery from the point of PP reprocessing, under optimum pyrolysis process operating parameters, the concentration of certain compounds other than propene produced from PP pyrolysis processes with substantial market price may qualify pyrolysis as a feasible recovery process (Ratcliffe, 1994). These kinds of polymers undergo pyrolysis process to produce valuable hydrocarbons (Duryodhan, 1996).

Although thermal and catalytic pyrolysis of virgin and waste PP were reported by several studies, as the demand of PP disposable cups is growing in most of the countries including the US (MacVey, 2017) and the UK (Circular, 2016), in this work, attention is paid to obtain optimum process conditions that favours for maximum yield of liquid fuel fractions from used disposable cups of polypropylene (PP) with and without the presence of catalyst in a simple batch pyrolyzer. The effect of temperature, feed to catalyst ratio, and reaction times on yield of liquid fuel fraction were studied in the catalytic process. Whereas in thermal process, the effect of temperature and reaction times on product distribution were carried distinctly. Temperature ranging from 500 to 850°C are required in thermal cracking (Filho et al., 2005; Kim et al., 2002), therefore, by keeping a constant heating rate at 15 °C/min, a range of 500 to 650 °C of temperatures was verified in thermal degradation process. As catalytic degradation requires lower temperatures from 350 to 550 °C (Filho et al., 2005; Marcilla et al., 2003), different catalysts such as natural and commercial zeolites (HY, HBeta, and HZSM-5), spent FCC, red mud from alumina refineries, and natural minerals ($CaCO_3$ and $NaCO_3$) have been used in catalytic pyrolysis of various types of waste plastics. Activated carbon was applied for the pyrolysis of LDPE and HDPE in the literature (Norbert et al., 2017) and showed slight increments than thermal process in the product yields and significant conversion of sulphur due to higher BET surface area (859 m^2/g). However, for this study, it was opted for the first time to apply on pyrolysis of waste PP. In AC catalysed process, the range of temperature applied was from 470 to 530°C while F/C ratio changed from 1 to 4. TGA was conducted to characterize the WPP plastics in the range of 25 to 700°C at atmospheric pressure. Catalyst was studied for its morphology and compositions by using XRD and SEM analysers. Thermo-Physical characterization of the liquid fuel fractions were performed to compare with conventional fuels (Panda & Singh, 2004).

2. Materials and experimental methods

2.1. Raw materials and catalyst

Waste PP materials were collected as disposable cups from various ceremonies organized in the college premises at NIT Rourkela, India. The sample is presented in Figure 1(a). Activated Carbon (A-C) catalyst material employed in this study was supplied by SS Enterprises, Rourkela, India. The sample is depicted in Figure 1(b).

2.2. Raw material preparation and characterization

2.2.1. Densification of WPP disposable cups

The disposable cups were cut into ½ in size and then melted into pellets/flakes in a cylindrical stainless-steel vessel of 17 lit capacity at a temperature of 150 °C for 15 min. A batch of 200 g of the sample produced 195 g (97.5 %) of solid pellets, with 5 g (2.5 %) was lost as emitted gases during the melting process. The molten solid material was then crushed into pellets ranging in size from 0.1 to 0.3 cm. The purpose of converting the waste PP materials into the form of pellets is to reduce the reactor volume for pyrolysis process and makes convenient to handle substantial quantities.

(a) (b)

Figure 1. Disposable cups as waste polypropylene plastics (a) and activated carbon as catalyst (b)

2.2.2. Characterization of WPP disposable cups

After reducing the size of the WPP disposable cups to 2 to 3 cm in accordance with ASTM D3172 methodology, the moisture, volatile matter, ash, and fixed carbon contents were determined. Fixed carbon, % = 100 – (moisture, % + ash, % + volatile matter, %)

To determine the composition of precursor materials, a CHNS analyser was used and estimated elemental composition of the samples and subsequently found the appropriate chemical formulae for further analysis of the materials.

Thermogravimetric analysis (TGA) was performed by operating DTA-Thermogravimetric Analyser, available at the Department of Chemical Engineering at N.I.T Rourkela. It was noted that the loss of mass per sec of time at a constant rate of heating 10 °C per min up to maximum temperature of 700°C. It was further analyzed by converting into weight loss fractions per min of time.

2.3. Analysis of A-C Catalyst

It was significant to examine the composition and morphology of all catalysts applied. To study the specific catalyst substances, XRD analysis was done by using X'Pert, the Philips Analytical X-Ray B.V instrument available at N.I.T Rourkela. Composition of Activated Carbon (A-C) catalyst materials was determined.

JEOL, JSM-6480LV Scanning Electron Microscope (SEM) analysis was performed for observing the nature of surface and porosity and to estimate the void fractions by printing their photographs with high resolution at 350 and 6,500 magnifications, corresponding to 50 µm and 2 µm respectively for scale of length.

3. Methodology

The cracking of dense WPP disposal cups was performed in the absence of air/oxygen by providing a perfectly sealed cylindrical batch reactor to examine the effect of temperature alone in case of thermal pyrolysis. The effect of change in temperature and Feed to catalyst (F/C) ratios in catalytic degradation were studied separately. Experiments were planned distinctly at different levels of temperatures in an ascending order to identify its effect on the yield of liquid product.

3.1. Thermal pyrolysis of WPP disposable plastic cups

The prepared precursors in the form of dense pellets/flakes of 100 g were taken into a cylindrical cast iron reactor of 300 ml of volume. The reactor, which was mounted inside the muffle furnace made by SHIMADEN CO. LTD. Japan, coupled with SR1 and SR3 series digital controller, was perfectly sealed with M-Seal for the prevention of any leakage of vapors.

With the aid of PID controller, the process temperature was set to identify its effect on process, in terms of reaction time and product distribution with a specific heating rate of 15°C/min. The vapors, leaving out of the reactor, were allowed through a ½ inch copper pipeline and subsequently condensed in a glass condenser by using water, mixed with ice circulated by a simple submersible pump as shown in Figure 2. Condensed liquids were collected in a measuring jar to quantify the volume of liquid fractions. The non-condensable gases were vented off through a water trapping system. The effect of reaction temperature on product distribution and reaction times were studied in between 500–650°C. Afterwards, physical characterization of liquid products was performed to estimate specific gravity, density, pour point and flash points.

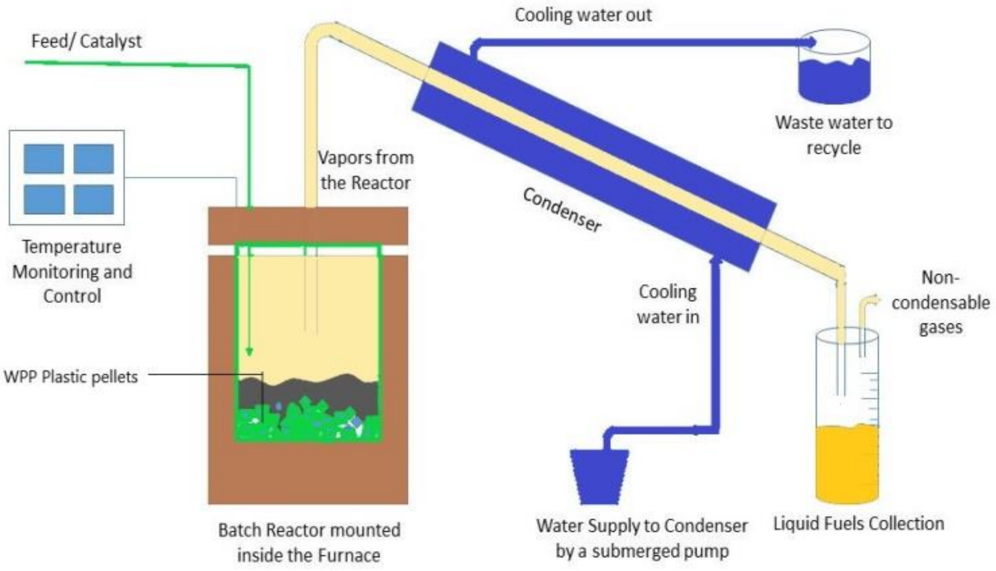


Figure 2. Experimental Setup for both thermal and catalytic pyrolysis of waste PP plastics

3.2. Catalytic pyrolysis of WPP disposable plastic cups

The effect of temperature and feed to catalyst ratio (F/C) on reaction time and product distribution were studied using Activated Carbon (A-C) catalyst in a simple batch pyrolyzer as shown in Figure 2. A constant heat rate of 15 °C/min, temperature range of 470–530 °C, and a range of F/C, 1-4 at atmospheric pressure were applied to detect their influence on the yield of products and their dissemination.

3.3. Characterization of liquid fractions

Thermo-physical properties such as density, calorific value, pour point, and flash point were measured according to a test protocol, IS 1448, to identify the fuel characteristics of liquid products and compared it with the conventional fossil fuels.

4. Results and discussion

Thermo-physical characterization of precursor materials, activated carbon catalysts, and liquid products were performed and analyzed. Experimental results were investigated to detect the effect of temperature and F/C ratios on liquid product generation.

4.1. Analytical results

4.1.1. Proximate and ultimate analysis of raw materials

Proximate analysis of precursor material, i.e., waste polypropylene plastics was revealed that they contain maximum volatile matter with less ash content as shown in Table 1. Ultimate analysis of the raw materials was done in terms of CHNS analysis which disclosed the elemental composition of the feed as shown in Table 2. The feed has potential amount of carbon (85%) and hydrogen (14.4%), and it does not have any nitrogen but has traces of sulphur. Based on the CHNS report, chemical formulae of the precursor material were formulated as $C_{7.0925}H_{7.197}S_{0.000813}$.

Table 1. Proximate analysis of WPP disposable cups

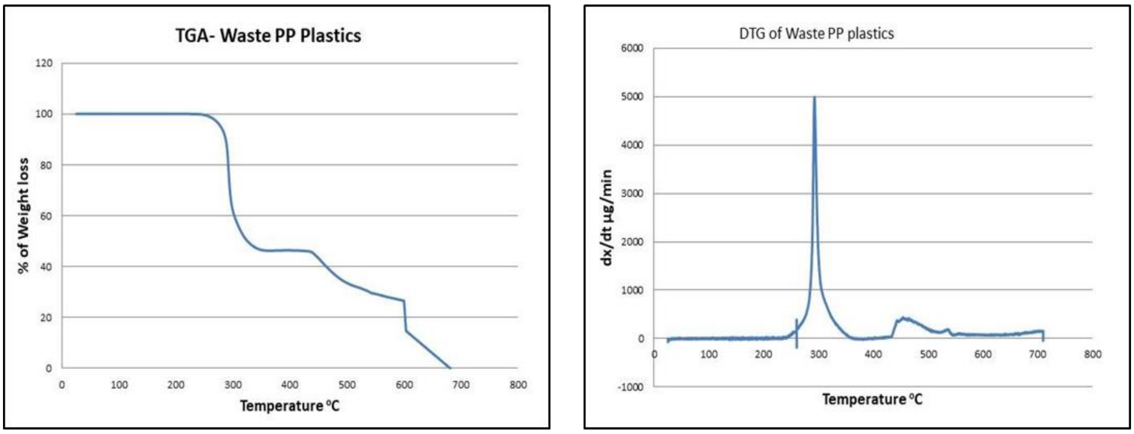
Material	Moisture %	VOM %	Ash %	Fixed Carbon %
Waste PP Plastics	5.8	85.44	1.03	7.73

Table 2. CHNS analysis of WPP disposable cups

Sample	C %	H %	N %	S %
Waste PP Plastics	85.11	14.394	0	0.026

4.1.2. TGA and DTG of WPP disposable cups

The changes in the mass of WPP plastic samples were studied in the temperature bounded between 25 to 700 °C with a constant heating rate of10 °C/min.



(a) (b)

Figure 3. TGA (a) and DTG (b) of WPP disposable cups

As depicted by Figure 3(a) and 3(b), there was no appreciable change in the mass until 240 °C of temperature. More than 50% of weight loss was noted between 240 and 335 °C, followed by sluggish rate of degradation until the temperature reached 430 °C. A gradual rate of decrease in mass reaching from 52 to 54% between 430 to 590 °C was observed.Aafter that, it was drastically collapsed to 86% during the change in temperature of 590 to 603 °C. And at the final stage, it was again sluggish until the mass vanished completely at 680 °C. The rate of change of mass at 292 °C was highest than any other as shown in Figure 3(a). To achieve higher yields, the experimental work was conducted at temperatures ranging from 470 to 650 °C for both thermal and catalytic pyrolysis studies.

4.1.3. Examination of Activated Carbon (A-C) Catalyst

XRD studies of selected catalysts were used to determine their compositions. For activated carbon, the peaks by the XRD are seen in Figure 4. Peaks at 24° and 42° indicate the presence of carbon quantity. The small peaks were the presence of some acids used to activate the carbon.

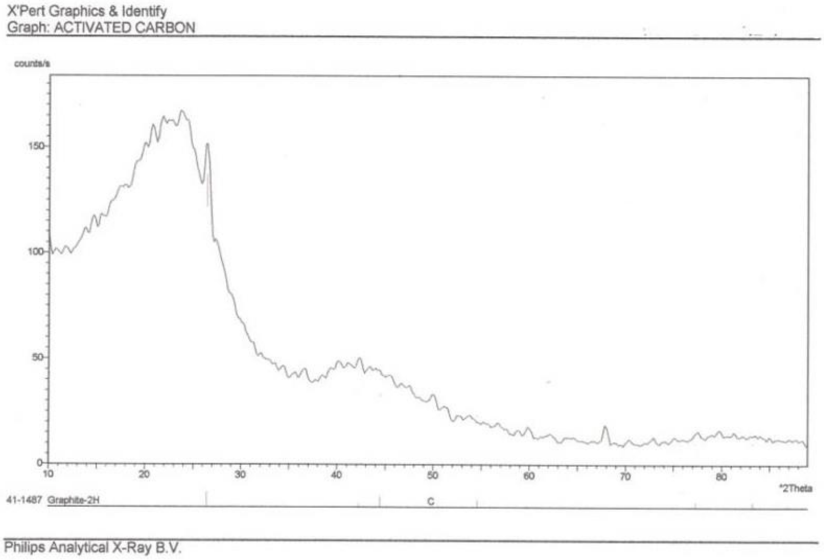
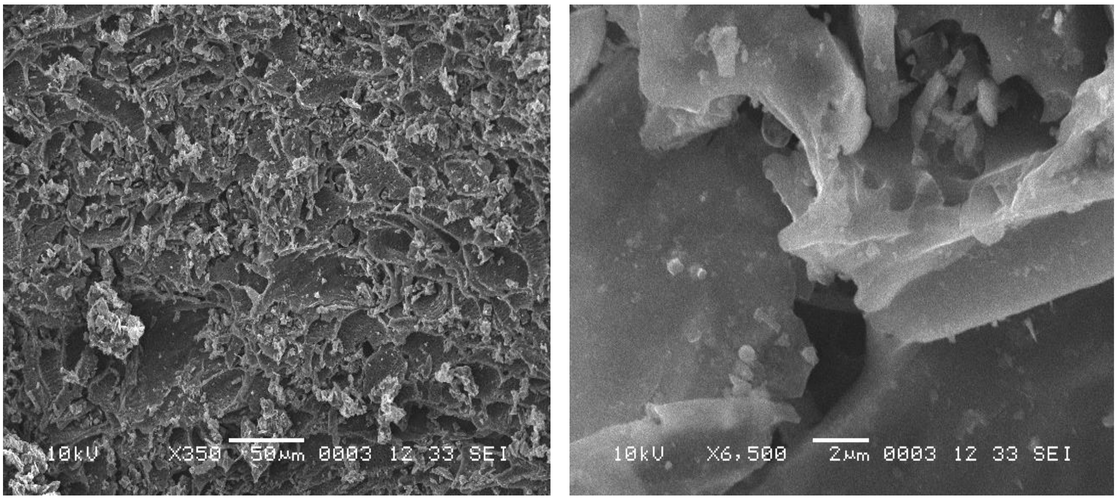


Figure 4. X-ray diffraction pattern of Activated Carbon (A-C)



(a) (b)

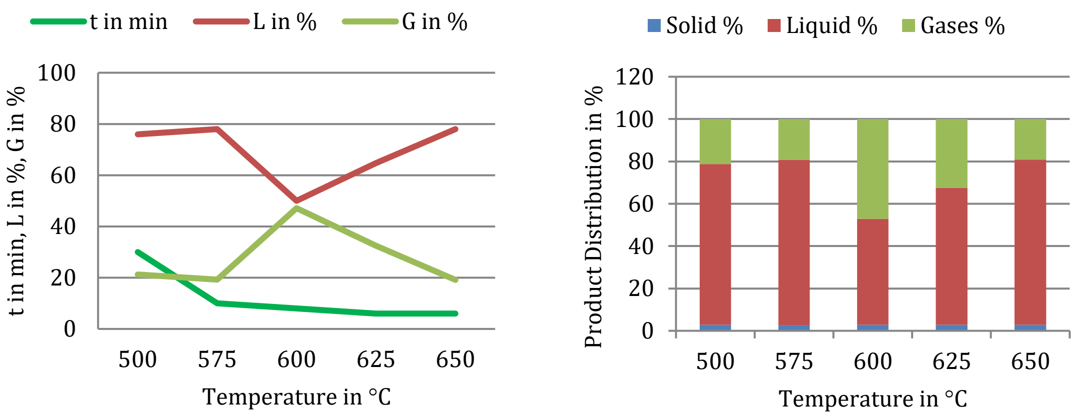
Figure 5. SEM photographs of Activated Carbon (A-C) at 350 magnitude (a) and at 6,500 magnitude (b)

SEM examinations of catalyst material revealed its structural properties. At 350 magnitude of resolution and at 10 kv for AC catalysts, the external surface was observed as uneven as displayed in Figure 5(a). It exhibits agglomeration and it had an amorphous surface. However, the nature of the distribution of pores, their porosity, and void fractions are clearly extrapolated from closer images of better resolution at 6500 magnitude (Figure 5(b)). The pores are not homogeneous and the particles are not uniform. The apparel pore size of activated carbon catalyst measured approximately as an average value of 2 μm based on its morphological studies.

4.2. Experimental results

4.2.1. Thermal pyrolysis of WPP disposable plastic cups

Thermal pyrolysis was conducted at higher temperatures to ensure maximum conversions and to study the effect of temperature on the yield of liquid fraction. The liquid fractions were higher at 500, 575 and 650°C. Although the liquid portion was slightly less at 500 °C, it was highly stable in liquid state, whereas at other temperatures the liquid yielded was unstable in its state and subsequently solidified into wax.



(a) (b)

Figure 6. Effect of temperature on reaction time, liquid fraction, and gaseous fraction (a), Effect of temperature on product distribution (b) in thermal pyrolysis

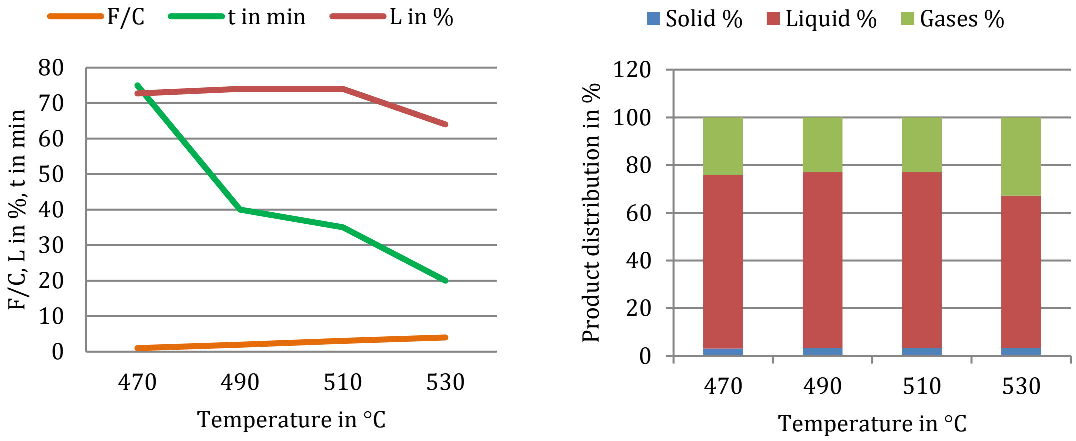
Table 3. Product distribution of thermal pyrolysis of waste PP plastics

Temperature in °C	% Solid	% Liquid	% Gases	Reaction time in min	Nature of liquid product
500	2.80	76	21.20	30	Stable liquid fuel
575	2.75	78	19.25	10	Wax
600	2.85	50	47.15	8	Wax
625	2.85	64.7	32.45	6	Wax
650	2.85	78	19.15	6	Wax

The influence of temperature on reaction time was also reported as 30 min at 500°C despite of 10 min at 575 °C and less than 10 min at all other higher temperatures with a constant heating rate of 15°C/min as described in Table 3. At 575°C, the energy consumption was cut drastically with the highest liquid fraction. However, it was unstable in its state and transformed into wax immediately. The lowest liquid (wax) yield accompanied with higher gas fraction at 600°C was noted as plotted in Figure 6. There was also not much change in the fraction of solid found at all temperatures.

4.2.2. Activated Carbon (A-C) catalyzed pyrolysis

Catalytic pyrolysis of WPP plastics was performed with Activated Carbon (A-C) catalyst to investigate the effect of Feed to catalyst (F/C) ratio and the impact of change in temperature on the yield of liquid product. The performance of A-C was examined in between 470 °C to 530°C with F/C ratio in the range of 1 to 4 as indicated in Table 4. Higher and similar liquid yield of 74% was obtained at both 490 and 510 °C with reaction times of 40 and 35 min respectively corresponding to the F/C ratios of 2 and 3. Further increase in temperature and in F/C ratio has drastically dropped the amount of liquid fuels to 64 % despite of lesser reaction time of 20 min. At lower reaction temperature of 470 °C, as depicted in Figure 7. It was noticed that the reaction time was too longer that indicate very slow reaction but resulted to 73% liquid fuel slightly lower than the best yield at 490 °C. Maximum gaseous fraction was found at the highest temperature of 530 °C with the highest F/C ratio of 4 whereas the solid fractions remained almost constant at all conditions.



(a) (b)

Figure 7. Effect of temperature on reaction time, liquid fraction and gaseous fraction (a), Effect Temperature on product distribution (b) in A-C catalyzed pyrolysis

Table 4. Product distribution of thermocatalytic pyrolysis of waste PP plastics using activated carbon catalyst

Catalyst	Feed/Catalyst	Temperature in °C	Time in min	%Solid	%Liquid	%Gases
A - C	1	470	75	3.09	72.72	24.19
A - C	2	490	40	3.2	74	22.8
A - C	3	510	35	3.2	74	22.8
A - C	4	530	20	3.2	64	32.8

4.2.3. Comparative study of Thermal and A-C catalyzed pyrolysis processes

Thermal and A-C catalyzed degradation processes were studied at optimum conditions as shown in Figure 8.

It was identified that the liquid yield was slightly more in the case of thermal cracking of WPP plastic cups at 500 °C with a residence time of 30 min and it was remained stable in its liquid state whereas in A-C catalysed cracking, with the feed to catalyst ratio of 3:1, the optimal product was obtained at 510 °C with a residence time of 35 min, slightly tardy than thermal conversion process due to aggregated particles and non-homogeneous porous structure despite the fact that it was not provided with any agitator. The product distribution and nature of the liquid product compared with other similar works is shown in Table 5. Ciliz et al. (2004) studied both virgin and waste PP degradation at 600 °C, while the present study was conducted at 500 °C but the liquid product yields were similar, except for gas and residue yields. Higher heating rates and reaction time lead to further fraction of condensable fraction into non-condensable gases. The waste on PP plastics that are recognized as impurities whose impurities became a dominant factor usually enhances the char forming reactions to promote the formation of residue at the expense of liquid products (Ciliz et al., 2004). Elevations in temperature lead to higher fraction of conversions into liquid, but in an unstable form. Condensation of vapors in ice-bath results in higher liquid fuels of higher viscosity reported at lower temperatures by Parku et al. (2020). Nevertheless, the comparison study reveals that the operating conditions of thermal pyrolysis such as range of temperature, heating rate, reaction time, presence of impurities, cooling media for condensation, and the design of the reactor are the effective radicals to determine the maximum rate of degradation and product distribution.

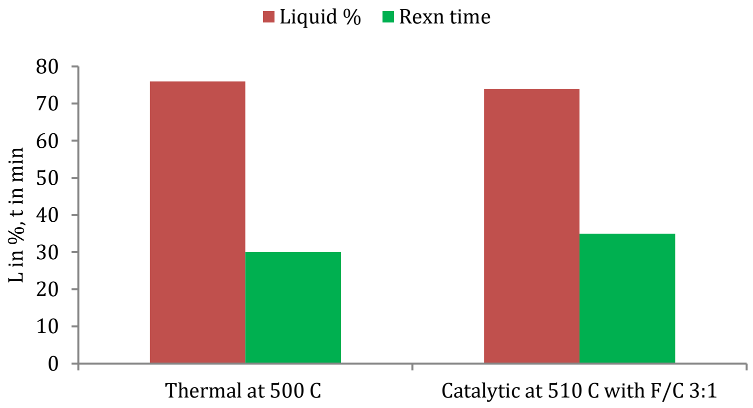


Figure 8. Comparison of liquid fraction and reaction times in both thermal and A-C catalyzed pyrolysis processes at optimal conditions.

Catalytic cracking of virgin PP reported by several studies using different kinds of materials, while catalytic pyrolysis of WPP was less focused. Some of the relevant studies were compared in Table 6. Zhao et al. (2020) performed thermal and catalytic degradation of virgin PP and reported that mesoporous molecular sieves of Fe-SBA-15 have strong catalytic activity that favored in reducing reaction time and improving product yield in addition to the strong cycle stability with a very low F/C value of 3:0.09. Although the Activated Carbon (A-C) has agglomerated (non-homogeneous porous structure), it has shown similar performance when it was applied for WPP in terms of productivity and reaction time. But it has higher F/C value of 3:1 and higher temperature range of 490-510°C. In another study conducted by Panda and Singh (2004), greater liquid fractions have resulted in catalytic degradation of virgin PP using Kaoline and Silica-Alumina at 450 and 500 °C, but at higher residential times of 70-75 min, subsequently demand for higher energy inputs compared with A-C catalyzed process which completed within 35-40 min. However, the aforementioned studies are not directly comparable if the presence of impurities and service life of WPP were considered as the major concerns.

In a report given by Lin and Yang (2007), catalytic degradation of WPP studied extensively using FCC catalysts in fluidized-bed reactor. Among FCC-s1, ZSM-5, HUSY, SAHA and Silicalite, the first three have shown better performance as they are compared in Table 6 using A-C. Almost similar F/C values are maintained, but applied temperature have 100-120 °C difference. The present study has operated at higher temperature without any mobilization facility for the material in the reactor. Yet, it has resulted in higher liquid and gas factions. Higher conversions obtained minimal solid content of 3.2%, unlike reported values of 12.2, 5, and 7.8% from the literature by Lin and Yang (2007). Nonetheless, performance of a catalyst in pyrolysis of WPP depends on the parameters such as surface area, pore size and shape, thermal stability, feed to catalyst ratio, reaction time, heating rate, and temperature.

Table 5. Comparison of thermal pyrolysis of WPP

Type of PP	Temperature (°C)	L (%)	G (%)	S (%)	Nature of Liquid	Reference
Virgin PP	600	76	11	13	--------	(Ciliz et al., 2004)
WPP	600	71	15	14	--------	(Ciliz et al., 2004)
WPP	488	84.4	9.9	5.7	Highly Viscous	(Parku et al., 2020)
WPP	800	86.33	-------	-------	Unstable	(Gaurh & Pramanik, 2018)
WPP	500	76	21.2	2.8	Stable	This Work

Table 6. Comparison of catalytic pyrolysis of WPP

Type of PP	Catalyst	F/C	Temperature (°C)	L (%)	G (%)	S (%)	Reference
Virgin PP	Fe-SBA-15	3:0.09	420-430	73-77	24-21	2-0.8	(Panda & Singh, 2004)
Virgin PP	Kaoline	3:1	450	89.5	9.75	0.75	(Panda & Singh, 2004)
Virgin PP	Silica-Alumina	3;1	500	91	8	1	(Panda & Singh, 2004)
WPP	FCC-s1	3;0.9	390	26.9	60.9	12.2	(Lin & Yang, 2007)
WPP	ZSM-5	3:0.9	390	38.8	56.2	5.0	(Lin & Yang, 2007)
WPP	HUSY	3:0.9	390	58.7	33.5	7.8	(Lin & Yang, 2007)
WPP	A - C	3;1	510	74	22.8	3.2	This Work

4.2.4. Thermophysical properties of liquid fuels

Liquid fuels obtained at optimal processes, a stable liquid product collected at 500 °C from thermal pyrolysis, and a liquid fraction obtained at 510 °C with F/C of 3:1 for A-C catalysed cracking, were tested for thermo-physical properties according to IS 1448 and reported in Table 7 along with the list of properties of most common liquid hydrocarbon fuels such as gasoline, diesel, and kerosene. It was noticed that the relative densities of hydrocarbon fuels derived from WPP disposable cups have similar figures with diesel and kerosene while their pour points match with gasoline and flash points are comparable to kerosene. The measured gross calorific values were slightly higher than the average heating values of conventional liquid fuels.

Table 7. Thermo-physical properties of liquid fractions

Property	Liquid obtained from thermal pyrolysis at 500 °C	A-C catalyzed liquid fraction at 510 °C with F/C of 3:1	Gasoline (API, 1976)	Diesel (USDOE, 2006)	Kerosene (MSDS, Gulf Oil Ltd Partnership)
Colour	Yellow	Yellow	Orange, Red	Clear, straw-yellow liquid	Clear
Specific Gravity @ 15 °C/15 °C	0.804	0.85	0.72 to 0.78	0.83 to 0.88	0.79 to 0.84
Density @ 15 °C in g/L	804	850	720-780	830 to 880	790 to 840
Melting Point/Pour Point in °C	-65	-80	< -60 (MSDS, Sinclair Oil Comp)	-12	-32
Flash Point by Abel in °C	33	31	-38 to -42	68 to 94	>38
Gross calorific value (MJ/kg)	46.5	47.1	45	44.27	44.19 (SEAI)

5. Conclusions

Characterisation of feedstocks, waste polypropylene (WPP) plastic cups through proximate, ultimate analysis, and TGA revealed that it has chemical formulae of $C_{7.0925}H_{7.197}S_{0.000813}$ and they degrade mostly (86% of original mass) in temperature ranged from 430-603°C. XRD and SEM were performed to characterise the activated carbon catalyst and it was discovered that the presence of carbon at major peaks with an apparent pore size of 2 μm based on morphological observation. Thermal and activated carbon catalyzed pyrolysis processes were employed for the degradation of waste polypropylene plastic cups and converted them into liquid fractions.

The effects of temperature and WPP plastics to catalyst ratios (F/C) on liquid product distribution and residence time were examined separately. The optimal liquid yields noted at 500°C and 510°C C in thermal and A-C catalyzed processes with F/C of 3:1 respectively. Despite of the fact that the liquid yields donot differ much from thermal process, they are highly stable. Liquid fractions collected in thermal pyrolysis process were highly unstable in their state and eventually transformed into wax, except at 500°C where its liquid state remained stable. The majority of thermo-physical properties of liquid fractions produced at optimal conditions are comparable with the properties of fossil fuels such as gasoline, diesel, and kerosene.

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