A Review: Catalytic Pyrolysis of Municipal Solid Plastic Waste (MSPW) for Production of Liquid Hydrocarbon Fuels

Shashank Pal, Shyam Pandey, Amit Kumar Sharma, and Rishabh Agarwal

Abstract The ever-increasing demand for polymers is posing serious issues in terms of controlling waste plastic disposal, which is also creating a threat to the environment. The thermal cracking (decomposition) of these waste polymers is considered a promising technique for converting these wastes into solid, liquid, and gaseous products. In the thermal decomposition, process catalysts play a vital role to optimize the yield of the liquid fuel. Many research has been conducted in order to find specialized catalysts and suitable operating parameters for a successful thermal cracking process. The purpose of the study is to review the current accomplishments and difficulties in catalytic thermal degradation of municipal solid plastic waste (MSPW) into lucrative liquid fuels as well as future prospects. Several studies have been done on various catalysts that are employed in processes, but studies on marketable and affordable catalysts could be important in establishing an economically feasible waste to fuel conversion system for commercial applications. As a result, the current review paper focuses on findings from advanced investigations completed over the last five years on various low-cost and environmentally friendly catalysts.

Keywords Municipal solid plastic waste · Catalytic pyrolysis · Hydrocarbon fuels

1 Introduction

Plastics are the most widely used material throughout the world. As per the CPCB report 2019–20, all states and UT produced plastic waste of 3,469,780 TPA. Figure 1 Shows the percentage distribution of plastic trash produced in various States/UTs. The state of Maharashtra generates the most plastic garbage, followed by Tamil Nadu and Punjab, in that order [1]. It offers a significant contribution to modern

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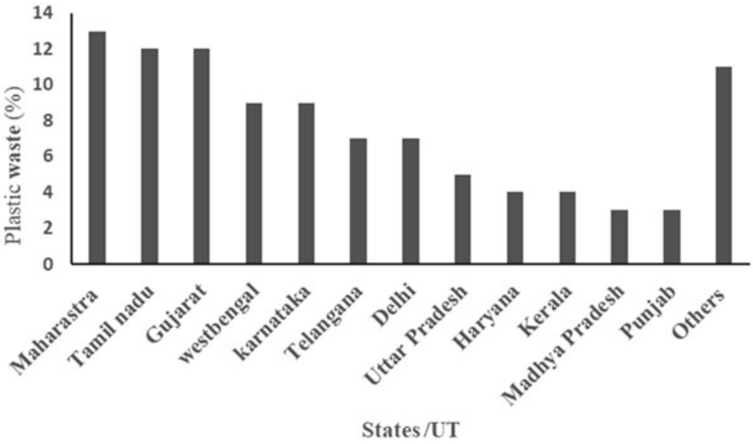

Fig. 1 CPCB report on the waste plastic generation of the year 2019–20 [1]

civilization, due to its durability, flexibility, and economical to produce and use [2]. However, its production (plastic and plastic waste) has increased due to the increasing population that also has been affected the natural resources and raised the demand for energy [3]. There is various kind of plastic such as low-density polyethylene (LDPE), High-density polyethylene (HDPE), Polypropylene (PP), polyethylene (PE), polystyrene (PS), polyethylene terephthalate is being used in making usable products for instance wrapper film, shopping bag, outfit, toys, plastic bottle, etc. Thus treatment of the mixed plastic waste is required to reduce and recovery of valuable products. There are various techniques of treating MSPW, thermal pyrolysis is a viable technique to produce valuable hydrocarbons of high calorific value [4]. The process is a cost-effective and environmentally friendly that offers both operational and environmental benefits. Such techniques are incineration, gasification, plasma gasification, combustion and pyrolysis, glycolysis, hydrolysis, aminolysis, and hydrogenation have been proposed by the researchers to minimize the MSPW and transform it into energy products [5]. Pyrolysis is one of the most effective and viable technology among other thermal decomposition techniques that produce oil, gaseous, and solid carbon black by heating MSPW at temperatures range 573–823 K in the absence of oxygen/air [5–7].

Thermal pyrolysis is an endothermic process that does not need any external agents. Catalytic pyrolysis is a catalytic process that requires external agents. Catalytic pyrolysis involves the use of catalysts as external agents to carry out the process [8]. The use of catalyst lowering down the temperature by decreasing the reaction activation energy [9]. Moreover, catalysts increase the production of the gaseous hydrocarbons (condensable and non-condensable vapors) by converting the heteroatoms into gaseous states and enhance the further racking of gaseous hydrocarbons to obtain the higher yield of liquid hydrocarbons [10]. Catalyst use diminishes the higher oil fraction and increases the gasoline fraction range C5–C12 in liquid hydrocarbons [11, 12].

Mochamad Syamsiroa et al. conducted the study on the pyrolysis process and transform it into liquid, solid, and gaseous hydrocarbon fuels to optimize the liquid hydrocarbons fuel that reduces the dependency on fossil fuels [13]. The yield of the hydrocarbon product in the pyrolysis process might be increased by adjusting process parameters such as heating rate, temperature, pressure, and a suitable catalyst. Miandad et al. conducted the study on the catalytic pyrolysis on different plastic waste and obtained the liquid yield of 60–70%, 40–54%, and 40–42% for polystyrene (PS), polypropylene (PP), and polyethylene (PE), respectively at temperature 550 °C with natural zeolite as catalyst [14]. Chika et al. studied the two-stage catalytic pyrolysis reactor with HZSM-5 as a catalyst and resulted that the non-catalytic process produced the liquid yield in the range of 81–97 wt%. However, introduced catalyst curtailed the liquid yield and produced in the range of 41–51 wt% with increasing in the gas yield due to the breakdown of the liquid volatile [15]. Jasmine et al. evaluated a broad variety of acidic and basic catalysts for the conversion of waste polyethylene, including silica, calcium carbide, alumina, magnesium oxide, zinc oxide, and a homogenous combination of silica and alumina. Based on reaction time, CaC_2 was superior, while the efficiency of conversion into a liquid for SiO_2 was determined to be highest in the case of LDPE under ideal circumstances. The findings of column separation using various solvents show that an oxide-containing catalyst is most suited for selective conversion into polar and aromatic compounds, whereas calcium carbide (CaC_2) is best suited for selective conversion into aliphatic products [16]. Catalytic pyrolysis plays a vital role in the thermal degradation of the waste plastic and reduces the activation energy. Catalysts, such as an acid catalysts, lower the activation energy needed to break these bonds by lowering electron density. In comparison to the non-catalytic method, they create completely different high-quality hydrocarbon fuels owing to the cracking process [17].

Hence, the present study focused on the effect of the catalyst on the hydrocarbon products such as liquid and gaseous hydrocarbon. In addition, insight into the upgradation of physicochemical properties of the liquid hydrocarbons with different catalysts has been addressed.

2 Thermal Pyrolysis Process

Thermal pyrolysis is the conventional process that is used to degrade or decompose waste plastic. It decomposes the long chain high molecular weight of the hydrocarbon atoms transforms them into shorter, low molecular weight compounds [18–20]. This process requires a higher temperature to break down the carbon–carbon and carbon-hydrogen bond in an inert atmosphere to obtain the solid, liquid, and gaseous fraction of hydrocarbons as end product [19, 21].

3 Catalytic Pyrolysis

Catalytic pyrolysis is a new addition to the conventional pyrolysis concept to improve the liquid yield and overall process efficiency. Introducing the catalyst in the process minimizes the activation energy and starts quick degradation of the long hydrocarbon chain at a lower temperature [22].

3.1 Effect of Catalytic Process on Liquid Hydrocarbons

Catalyst is essential in the MSPW pyrolysis process. It is capable of cracking the hydrocarbon chain faster at extremely low temperatures than the thermal pyrolysis method. As shown in Fig. 2 that different waste plastic has different oil production capacities at various temperatures. The yield of liquid oil depends on the volatile matter of the feedstocks, higher volatile matter leads to a higher liquid yield [23].

In addition, Different types of catalysts have different impacts on pyrolysis process, as shown in Fig. 3. HDPE with MCM 41 and ZSM-5 given a higher liquid yield of approximately 95.8 wt%. [24]. Similarly observing the municipal mixed plastic waste produced the higher liquid hydrocarbon approximate 81–97% with HZSM-5 as compared to other catalysts used in the pyrolysis of mixed plastic waste [15]. Various study has been carried out on the catalytic process with different catalysts such as zeolite, bentonite, red mud, and clay. The utilization of the zeolite catalyst in the process provides a higher yield of liquid hydrocarbons. Its crystalline microporous structure and acidity increase the reaction rate of the hydrogen transfer that was suitable for producing high conversion of the gaseous hydrocarbons at a low-temperature range between 350 and 500 °C [25]. Table 1 depicts the influence of

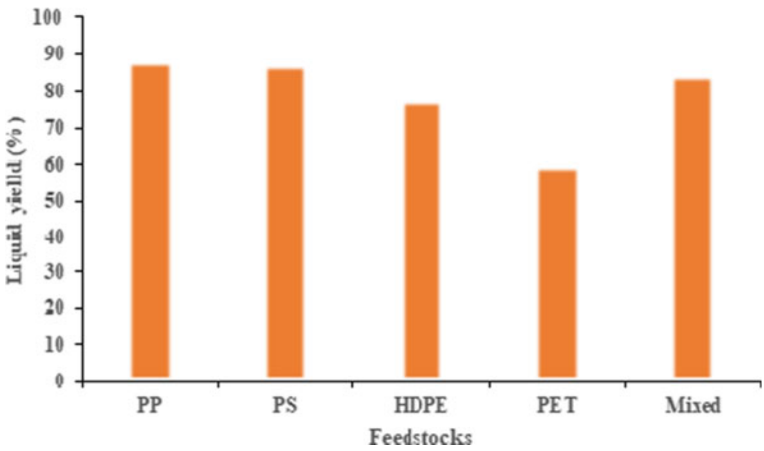

Fig. 2 Thermal pyrolysis at temperature between 400 and 700 °C temperatures

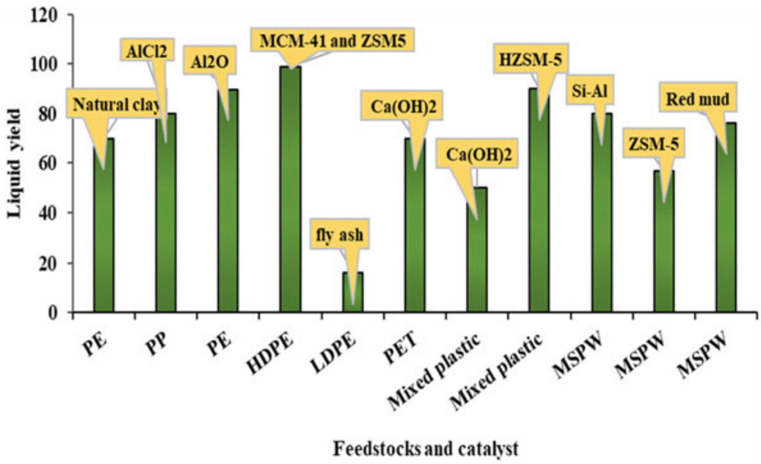

Fig. 3 Catalyst effect at temperature 400–500 °C [15, 26–34]

catalysts on the solid, liquid, and gaseous hydrocarbons produced during the catalytic pyrolysis of municipal mixed plastic waste.

3.1.1 Effect of Catalytic Pyrolysis Process on Gaseous Hydrocarbon Yield

Catalytic pyrolysis also affects the gaseous hydrocarbon of municipal mixed plastic waste as depicted in Fig. 4. These uncondensed gaseous are the mixture of carbon monoxide (CO), carbon dioxide (CO_2), Hydrogen (H_2), methane, ethane, ethene, propane, butane, and other hydrocarbons gases [38, 39]. From the figure, it is concluded that propane is the main fraction of the pyrolysis gaseous hydrocarbons. The catalyst ZSM-5 used in the pyrolysis process increases the gaseous hydrocarbon fraction than the thermal pyrolysis process. It may be possible due to the shape selectivity of the catalyst [17]. In addition, red mud used in the pyrolysis process produced a higher propane fraction and diminishes the proportion of other hydrocarbons. This may occur due to the hydro-cracking reaction. The catalytic activity of Fe_2O_3 in red mud as a catalyst in catalytic pyrolysis increases CO_2. While ZSM-5 and red mud both produced higher hydrogen gas than thermal pyrolysis, which may occur due to the hydrogen abstraction during the aromatization reaction [40].

3.1.2 Effect of Catalytic Pyrolysis on Physicochemical Properties of the Obtained Fuel

The catalytic process has a wide impact on the physicochemical properties of the obtained liquid hydrocarbons. Catalyst contributes to extracting good quality liquid

Table 1 Effect of catalyst on yield of liquid, gas, and solid hydrocarbons

Feedstock's	Catalyst	Temperature (°C)	Yield	Author
Mixed plastic waste	Natural zeolite (70%) and bentonite (30%)	500	53.2% (L) 9.12 (S) 458.82 (G)	Sembiring [35]
Mixed plastic waste with PVC	FCC-R1	390	4.9 (L) 11.7 (S) 81.7 (G) 1.7 (HCl)	Lin [36]
Mixed plastic waste with PVC	HZSM-5	390	4.2 (L) 6.4 (S) 87.9 (G) 1.5 (HCl)	Lin [36]
MMPW	Si/Al = 1:3	420	54.34 (L) 20.52 (S) 25.14 (G)	Wang [37]
PP, PE, PS, PET, PVC	ZSM-5	500	39.8 (L) 1.8 (S) 39.8 (G)	Lopez [34]
PP, PE, PS, PET, PVC	ZSM-5	425	61.2 (L) 7.5 (S) 31.3 (G)	Lopez [34]
PP, PE, PS, PET, PVC	Red mud	500	57.0 (L) 1.7 (S) 41.3 (G)	Lopez [34]
PP, PE, PS, PET, PVC	Red mud	440	76.2 (L) 2.2 (S) 21.6 (G)	Lopez [34]
MMPW	Cement	450	82 (L) 18 (G)	Obeid [29]
MMPW	Silica sand	450	40 (L) 9 (S) 51 (G)	Obeid [29]

hydrocarbons ranging from C_5 to C_{11} that is close to conventional fuel (gasoline and diesel). However, conventional thermal pyrolysis produced the liquid hydrocarbon range C_5–C_{23} [41]. Thereby catalytic pyrolysis process has importance to produce the higher gaseous hydrocarbon up to a certain catalyst concentration and temperature range 400–550 °C above the temperature 600 °C no liquid yield is obtained [42]. It concluded that catalyst concentration with a tailored temperature range might affect the yield of the liquid hydrocarbon as a result of carbon deposition on the catalyst surface. Despite the fact that breakdown of plastic waste begins at a relatively low temperature in the presence of the catalyst, and it is found that higher catalysts might be left the higher by-products than liquid yield. Figures 5, 6, and 7 introduced the catalytic pyrolysis of the MSPW effect on liquid hydrocarbons fuel density, viscosity, and calorific value with different catalysts and it is found that thermal

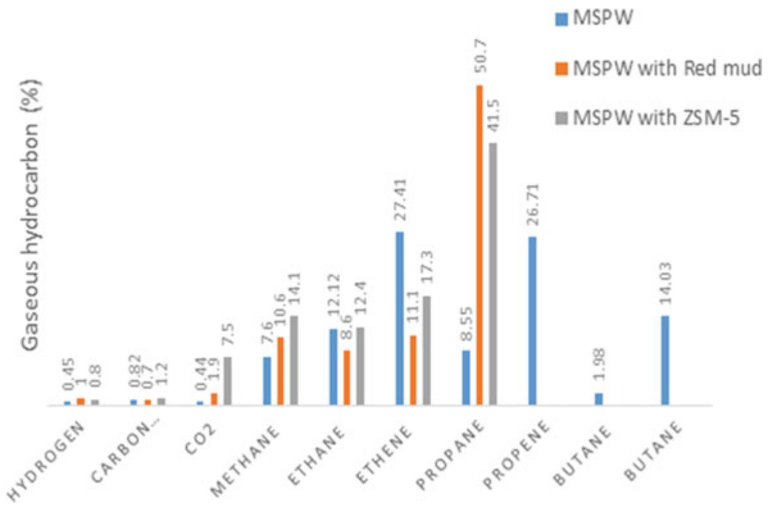

Fig. 4 Effect of catalyst on gaseous hydrocarbon [17, 34]

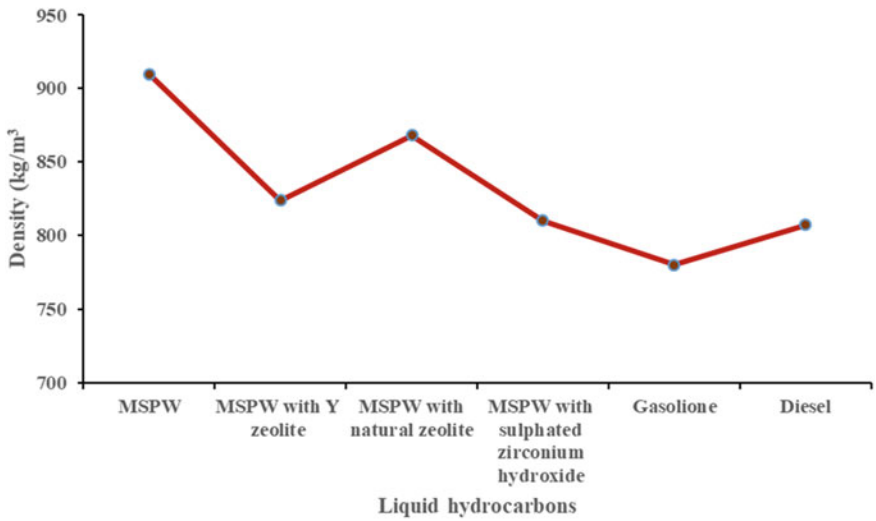

Fig. 5 Effect of liquid hydrocarbons with and without catalyst on density [13, 16, 43]

pyrolysis of MSPW derived the fuel of higher density and viscosity with low calorific value [43]. However catalytic pyrolysis process especially with a zeolite has a good consequence with lower density and viscosity with the higher calorific value of liquid hydrocarbons by producing the lighter and smaller hydrocarbons fractions [44]. These physicochemical properties of liquid hydrocarbons are essential in the application of an internal combustion engine.

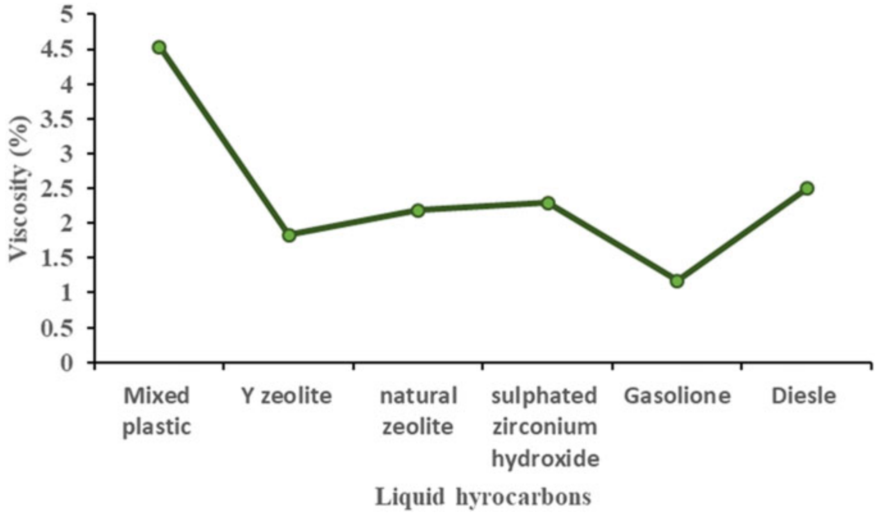

Fig. 6 Effect of liquid hydrocarbons with and without catalyst on viscosity [13, 16, 43]

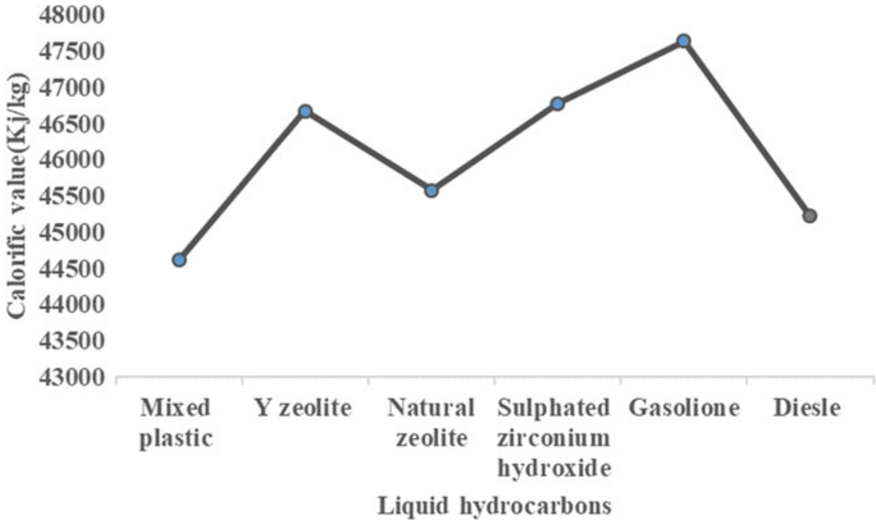

Fig. 7 Effect of liquid hydrocarbons with and without catalyst on calorific value [13, 16, 43]

4 Conclusion

The extensive study of the state of art elaborates the effect of different catalysts on municipal solid plastic waste to complete the pyrolysis reaction. Liquid fuels produced during catalytic pyrolysis are of higher quality that has low density and viscosity as compared to conventional thermal pyrolysis. Moreover, the employment of multiple catalysts improves process efficiency by improving the quality of the liquid oil and gases while decreasing process temperature and retention time. ZSM-5, HZSM-5, FCC, Al_2O_3, and Red Mud are the utmost extensively used and found substantial catalysts for MSW pyrolysis. However, tweaks such as thermal, acidic, and wet impregnation of metal may improve the catalytic activity of the catalyst by increasing its properties.

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