A Critical Appraisal of Techniques for Production of Liquid Fuel using Plastic Waste

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Abstract- **Plastics are synthetic product produced from a wide range of polymers such as polyethylene, polyvinyl chloride, nylon etc. The property that makes it so ubiquitous to use is that it can be moulded to the desired shape and once is set can serve the desired purpose. Plastics are lightweight, inexpensive and durable materials, which find its use in a wide range of applications. The easy availability of plastics has led to its exploitation and careless use. This excessive usage caused the accumulation of huge amount of plastic waste into the environment. Plastics have a very high life in the environment and do not disintegrate through the natural process in the environment. So, the plastic disposal without any effective technique accumulates the waste into the environment certainly causing pollution. Researchers have shown that since plastics are a product of petroleum they have the efficiency to be used for fuel production which will solve the problem of plastic disposal and the rising fuel crisis. The review of past studies related to the fuel production from waste plastics, plastic waste disposal techniques, sources of alternative fuel and waste management technologies aims to find out the best technique for waste plastic disposal and a source of alternative fuel using the discarded plastics as feedstock. This would solve the problem of plastic waste disposal and fuel crisis in a country.**

Key words: Pyrolysis, Plastic waste management, Alternate fuel, Effective plastic disposal.

I. INTRODUCTION

Plastic wastes have the potential to be turned into a valuable alternative source of energy production. True recycling of the waste materials occurs only by the conversion of the wastes into the products of use that can be effectively reused. This would also reduce the cost for waste collection, sorting and processing. The average consumption of the various types of plastics worldwide is found to be 35% of high density polyethylene (HDPE), 23% of polypropylene (PP), 10% of polystyrene (PS), 13% of polyvinyl chloride (PVC), 7% of polyethylene terephthalate (PET) and 12% miscellaneous polymers. However, PS and PP are the most prevalent in the waste polymer stream [1]. The plastics have more calorific values than the most prominent fuels like coal and gas. PP, PE and PET had heat capacity of 46.4, 47 and 46 MJ/kg, respectively while petrol, coal and natural gas had 44, 26, and 36 MJ/kg, respectively [2,3]. Plastics are also reported to undergo photo degradation i.e. it disintegrates into small fragments and disperses into the environment finally entering the food chain and causing health hazards.

In this paper various processes like gasification, liquefaction, pyrolysis, hydrogenation, thermal cracking and catalytic cracking are reviewed listing the advantages and shortcomings of each. These processes are called as feedstock based recycling of plastic and rubber waste which are reported to give liquid fuel as the product that has large amount of applications. This would in turn solve the problem of waste plastics disposal and mounting fuel crisis.

II. PLASTIC WASTE MANAGEMENT

Plastic waste management is one of the most prominent issue concerning the use and disposal of the polyethylene products. There are practices like reuse and recycling of the plastics to reduce the wastes in the environment, but since the recycled plastic cannot be used to produce the product of the same quality, so process like pyrolysis and thermo-catalytic conversion is a viable solution for the plastic waste disposal [4]. In Australia 20.8% of plastic waste was recycled during 2012-2013 [5]. United States alone generated around 39.3 million tonnes of plastic wastes in the year 2011, out of this only 6.8% i.e. 2.66 million tonnes was recycled and 82.7% was dumped as landfills [6]. United States, Japan along with China and India to produce more and more plastic waste and proclaimed that the rate of production is increasing rapidly [7].

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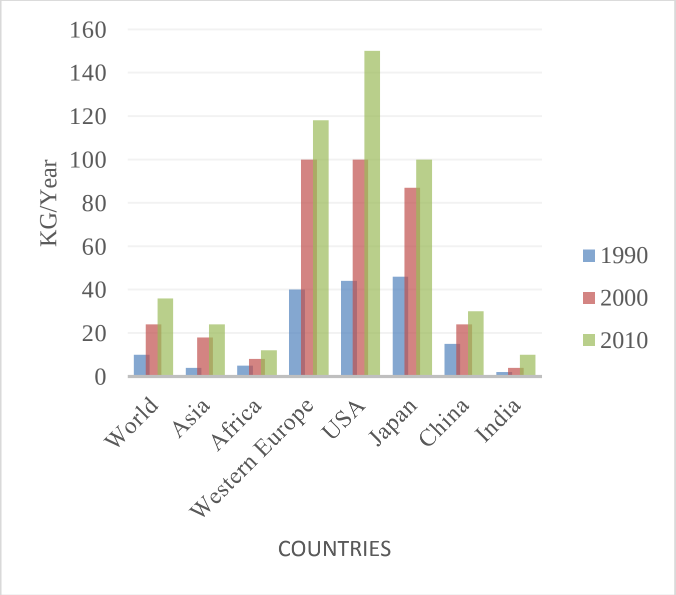

Fig. 1 Regional per capita plastic consumption data (kg/year) [8].

The graph shows the plastic consumption per person in kg/year. As it can be seen there has been a rapid increase in the plastic consumption rate from the year 1990 to 2000. United States being the most plastic consuming country and India is the least. But due to industrialization the plastic consumption is increasing very rapidly and so it the waste that needs to be disposed. Around 60% of the waste plastic produced is recycled which is also subjected to a serious constraint i.e.; financial source for the recycling of plastic is very limited. Also, the non-recyclable plastic wastes are one of the major concerns as they pose serious health and environmental issues [9]. These wastes are either subjected to incineration or land filling but, incinerating them emits toxic fumes of methane, chlorine, dioxins, carbon monoxide, hydrochloric acid etc. Techniques like thermal degradation, pyrolysis and thermal-catalytic cracking aim to convert the waste to resource rather than being a burden. By 1980s India recycled almost 60% of its plastic waste being the highest among the developed countries like Japan and United States [10]. Surprisingly Japan and United States recycled 5% and 1%, respectively of its plastic waste because they disposed the waste largely by incineration. In China, an oil refinery situated in Hunan province succeeded in procuring 20,000 tonnes of fuel from 30,000 tonnes of waste plastic using thermal pyrolysis [10].

A. Techniques for Plastic Waste Disposal

The commonly used techniques for the disposal of plastic waste are listed below.

1) Landfills

The disposal of plastic wastes by landfilling is one of the most common techniques used and it is preferred over incineration because it does not use high amount of energy as required by the incineration process. In this process, the non-recyclable plastic waste is disposed in alternate even layers of waste and soil into a pit which is then covered with a thick layer of soil. Landfilling of the plastic wastes not only occupies valuable space but also decays the fertile soil and leads to the unstable environment [11]. Many countries have already banned the landfilling process due to lack of landfill sites and non-availability of standards to dump the waste [12]. Chemicals like Polybromidateddiphenyl ethers, Bisphenol and Nonylphenols are used as catalysts to produce polymers [13]. These chemicals are very harmful and are found to be hormone disruptors [14]. Bisphenol is widely used in manufacturing of beverage bottles and it causes cardiac diseases, liver enzyme dysfunction and diabetes [15]. A report by American Chemistry Council (ACC) claimed that the use of all land filled plastics throughout the United States for fuel production could replace the use of 108 million tonnes of coal [16].

2) Incineration

Incineration is the ultimate disposal technique for plastic wastes [17, 18]. In this process, the waste is burnt at very high temperature for a very small duration (2 sec and 850˚C) and the ash is disposed by landfilling. The gases exhausted during incineration of plastic waste have pollutants like SO_x, NO_x, CO, CO_2, volatile organic compounds (VOC), particulate matter (PM) and polycyclic aromatic hydrocarbon (PAH) [19]. The ash of incineration is carcinogenic in nature [16]. So that will cause health hazards and disposal problems for the residue.

III. THERMAL DEGRADATION OF PLASTIC WASTES

As the name, itself suggests degradation of plastic wastes under high temperature and presence of catalyst based on the process requirement.

A. Thermal cracking (Pyrolysis and Liquefaction)

The process of pyrolysis and liquefaction are differentiated based on the gas used for the process. The thermal cracking process solely in the presence of nitrogen(N_2) gas is known as pyrolysis and when the process undergoes in the presence of hydrogen(H_2) gas it is called as liquefaction [20]. The thermal cracking of different types of plastics at a temperature of 500˚C in a stainless-steel reactor for 1 hour at 0.2-10Mpa of N_2 for the first time and 1Mpa of H_2 for the second time. It resulted in more yield (liquid fuel) for the second process [20]. So, this concludes that the use of hydrogen as the gas during thermal cracking gives out more yield.

Pyrolysis as the thermal dissolution of the carbonaceous material in an oxygen-deprived and a very controlled atmosphere. The Pyrolysis of plastic wastes will liberate fumes that may be cracked to any suitable catalyst at a temperature of 300˚C to 450˚C which are condensed to procure pyrolytic oil, which is further distilled to obtain gasoline, diesel, naphtha and kerosene [21]. Pyrolysis is a safe way to produce hydrocarbon fuels from waste plastics which could be used as a transportation grade fuel either by mixing with the conventional fuels or alone. Only the properties of the fuel like ash content and viscosity needs to match the stipulation of the fuel user's engines and country norms. No additives are required for the fuel if used for the boiler. The only necessity is of a skillful operator and a well-equipped facility because the process involves the production of highly flammable liquid and gases. This process of thermal degradation involves the heating of waste plastics and melting it to form liquid slurry, this thermal liquefaction of slurry occurs at a high temperature of 300˚C to 400˚C, distilling this slurry in the presence of catalyst or without catalyst as per requirement and finally condensing the liquid slurry to get liquid fuel as the product [21].

Pyrolysis of PVC emits toxic wastes that are both corrosive and have hazardous effects on environment. PVC's also gave high amount of residue and liquid fuel but had a low octane rating to be used as transport grade fuel [22]. The only issues with pyrolysis process are: requirement of cleaning of the reactor is too often, plastics have a very poor heat conductivity, the higher the load higher is the processing time, expenditure on catalyst is high, flash point of fuel produced by pyrolysis is lower than that of diesel (45˚C to 53˚C) and the produced fuel is intolerant to be used in the engines directly [23]. The optimal temperature for producing diesel and gasoline type fuels is 390˚C to 420˚C, also the technique need to be improved as the fuels cannot be used directly as transport fuel [24, 25]. An experiment on a very small scale where the feeding of waste plastic varied from 350gm to 5kg with a double condensation process gave gasoline at 200˚C to 240˚C and diesel at 240˚C to 360˚C [11]. The fuel production process was found to liberate some gases mainly methane, butane, ethane and propane which can be used again to heat up the reactor and the residue left is very less having binding properties so that can be used road repairing and roof surfacing.

B. Thermo-catalytic cracking

The process of thermo-catalytic cracking is like thermal cracking but a suitable catalyst is used to get the get better results than the latter process. Thermo-catalytic cracking is also known as hydrocracking. Catalysts readily reduce the total amount of energy needed for the activation of feedstock thereby directly reducing the temperature that is required for the process. Catalysts also increase the reaction rate of the feedstock. A combination of thermal cracking and catalytic cracking can be used to give out good quality of fuel and the thermo-catalytic process has a commercial grade potential to produce transport fuel [26]. Since the recycled plastic can't be used to produce the product with the same quality, so thermo-catalytic process is a viable solution of plastic waste disposal. The type of catalyst that needs to be used in the catalytic-cracking process depends on the quality of fuel needed, types of plastic used and availability of catalyst. Researchers have used different types of catalysts to obtain different results. An experiment to convert the waste LDPE to fuel using natural zeolite as the catalyst [27]. The efficiency of zeolite was enhanced by treating it with monometals and bimetals. This study showed that use of monometals and bimetal treated zeolite as catalyst for hydrocracking of LDPE results a better stable environment during process and the process can be carried out at a low temperature than thermal cracking making the process efficient and economically sound. The experiment using silicate as catalyst to melted plastic gave 85% of fuel as transport grade diesel and 15% as gasoline. This process is also called as Smuda process [10]. For catalytic and thermo-catalytic cracking both silica-alumina (SiO_2-Al_2O_3) and zeolites can be used to change the nature and the volatility for the obtained pyrolytic oils [28]. Na-zeolite ($Na_2Al_2Si_3O_{10}\cdot 2H_2O$) was found to performs de-halogenation more effectively [29]. Zeolite based catalyst give higher yield than non-zeolite based catalyst as they have high acids [30]. The ratio between catalyst and polymer controls the entire reaction, the catalyst more than the optimum range reduces the yield of the process [31].

There are number of zeolite based catalysts that are used and which produce different results based on their nature. Catalysts like silica-alumina [32], zeolite socony mobil-5 (ZSM-5) [33], barium carbonate ($BaCO_3$) [34] and Al-Zn composites [35] were used for the cracking process but Al-Zn composites are not feasible for industrial grade production of fuel since the cost of the catalyst is very high ultimately making the production cost of fuel very high [36]. A mixed plastic as feedstock and 5% of zinc oxide (ZnO) by weight at a temperature of 200-430˚C yields about 50.08% of fuel [37]. This catalyst produced 50.08% of fuel with a very small amount of residue. So, it can be used as the technique for production of liquid fuel. A mixture of plastics with equal weight of tire as the feedstock at a temperature of 250-430˚C with 2% of ferric carbonate ($Fe_2(CO_3)_3$) by weight as the catalyst [38]. This gave out 47.4% of fuel with a large amount of residue. Since the feedstock also has tires it generated a large amount of residue almost 37.7% of the total product. Due to this result tires are not recommended to be used along with the plastics for fuel production. Tires limit the entire process and decrease the efficiency of the process. The polypropylene as feed and Kaolin clay (SiO_2 43.12%, Al_2O_3 46.07%, MgO 0.027%, CaO 0.03%, Zn) as catalyst at 400-500˚C gave a yield of 87.5% of weight as fuel [7].

Kaolin clay as a catalyst gives the maximum yield for HDPE waste at a temperature of 400-500˚C [39]. The amount of residue during this process is substantially low and so it is highly recommended for use. A liquid fuel from plastic wastes tested it in an actual diesel engine which gave the brake thermal efficiency of 14% to 30% which is relatively low and reported that further technical assistance is required to boost the efficiency of the fuel [40].

IV. DISCUSSIONS

Every country in the world is facing severe continuous accretion of plastic wastes in the garbage dumping places. The problem is even more serious in developing and populous countries as they lack stringent laws for the processing of plastic wastes. The processes like landfilling and incineration solve the problem up to certain extent but they also pose some serious threats like ground water pollution, chocking of sewers, pollution by exhaust gases and soil contamination. So, these processes are not a complete solution to the plastic waste management.

Thermal cracking or pyrolysis of Low Density Polyethylene (LDPE) produces high percentage of volatiles that can entirely be converted into liquid oil. On the other hand, pyrolysis of Polyvinyl Chloride (PVC) produces more char but it also liberates huge amount of Hydrochloric Acid

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(HCL) which require a treatment before they are released into the atmosphere. So, a pyrolysis reactor using PVC as feedstock is more efficient but the system needs to have a downstream treatment process for acid vapours this can be done by light gas cleaners like $NaHCO_3$, AgNO3, NaOH etc. Types of plastic used governs the entire process of pyrolysis; less dense polymer require more temperature for the pyrolysis process. Pyrolysis has many drawbacks like cooking of the reactor wall, sticking of melted plastic on the reactor walls reducing the transfer efficiency of the reactor and lowers the yield of liquid fuel. To overcome these problem stirrers, need to be used also timely cleaning of the reactor is very essential.

The thermal-catalytic cracking is an advantage over the conventional pyrolysis process because it reduces the temperature required for the activation of the feedstock making the process more viable. The process of thermal-catalytic cracking can be used with liquefaction to increase the both quality and quantity of the yield. This also reduces the amount of catalyst used in the process, and keeping the economy in mind the process is made financially sound.

V. CONCLUSION

Pyrolysis of plastic wastes is found to be an effective technique for plastic waste management but it is not efficient as it requires a very high temperature for the conversion of the feedstock to fuel. Liquefaction process can be used for thermal-cracking of plastic waste as it makes the process efficient than pyrolysis by reducing the high temperature required for the process. Thermo-catalytic cracking of plastic waste is the most productive technique to convert the plastic wastes to liquid fuel. Zeolite based catalyst give higher yield because they have high acids. The reaction is controlled by the ratio between catalyst and polymer, the catalyst more than the optimum range reduces the yield of the process. The frequently used zeolite based catalysts are silica-alumina, ZSM-5, $BaCO_3$ and Al-Zn composites but these are not feasible for industrial production of fuel because the production cost of fuel goes very high. Kaolin clay used as the catalyst reported the maximum yield of 87.5% of output as fuel. The other frequently used catalysts are silica-alumina, zinc oxide, zeolites etc.

So, the process like thermal cracking and thermo-catalytic cracking have potential to produce liquid transport grade fuel that will reduce the ascending pressure on the fossil fuels. This will also solve the problem of plastic waste management and since the residue of the process has binding properties so it can replace bitumen in pavement construction and can also be used as repair material. The only limitation to the catalytic cracking is the cost of catalyst that is to be used for the process. Catalyst like zeolites give maximum yield but cannot be used for the fuel production on an industrial grade as its cost is very high and it is also needs processing before its use. This technique needs further advancement because the source of an alternative fuel will ease the fuel crisis in a country producing a large amount of plastic waste.

REFERENCES

[1] Tukker, A., Groot, H., Simons, L. and Wiegersma, S. “Chemical Recycling of Plastics Waste (PVC and other resins)”, The Netherlands: TNO Institute of Strategy, Technology and Policy, 1999.
[2] Mella, J. “Recycling of Polymers”, Department of Process and Environmental Engineering (2005). p. 1-9, 2005.
[3] Aguado, J. and Serrano, D. “Feedstock Recycling of Plastics Waste”, The Royal Society of Chemistry, 2006.
[4] Williams, P. “Waste Recycling: Waste Treatment and Disposal”, John Wiley and Sons Ltd. Second Edition. p.70-127, 2005.
[5] Vard, D. and Allan, P. “National Plastics Recycling Survey: Australia”, Sustainable Resource Use Pty Ltd. Carlton, Australia, 2014.
[6] Themelis, N. and Mussche, C. “2014 Energy and Economic Value of Municipal Solid Waste (MSW), Including Non-Recycled Plastics (NRP), Currently Landfilled in Fifty States”, Earth Engineering Centre, United States of America, 2014.
[7] Panda, A. and Singh, R. “Experimental Optimization of Process for the Thermo-Catalytic Degradation of Waste Polypropylene to Liquid Fuel”, Advances in Energy Engineering. 1(3). p.74-84, 2013.
[8] Panda, A., Singh, R. and Mishra, D. “Thermolysis of waste plastic to liquid fuel: A suitable method for plastic waste management and manufacture of value added products- A world prospective”, Renewable and Sustainable Energy Reviews. 14(1). p. 233-248, 2010.
[9] Makker, A., Gupta, A. and Gupta, L. “Plastic Waste in India-Management and Utilisation”, Energy Technologies, Climate Change and Sustainability. [Online]. p.79-86. ISBN: 978-93-83083-87-9, 2014.
[10] Alla, M., Ahmed, A. and Abdalla, B. “Conversion of Plastic Waste to Liquid Fuel”, International Journal of Technical Research and Application. 2(3), p. 29-31, 2014.
[11] Sarker, M. Rashid, M. and Molla, M. “New Alternative Vehicle Hydrocarbon Liquid Fuels from Municipal Solid Waste Plastics”, Journal of Fundamentals of Renewable Energy and Applications, 2011.
[12] Maria, F. and Pavesi, G. “RDF to energy plant for a central Italian region SUW management system: Energetic and economical analysis”, Advanced Thermal Engineering. 26(11). p. 1291-1300, 2006.
[13] Sarker, M. and Rashid, M. “Alternative Liquid Hydrocarbon Fuel Production: Comparative Study for Polypropylene Waste Plastic and Standard Plastic”, Energy and Power. Stamford, USA, (2013).
[14] Halden, R. “Plastics and Health Risks. Annual Review of Public Health”, Arizona, United States of America. 31(1). p. 179-194, 2010.
[15] Lang, I., Galloway, T., Scarlett, A., Henley, W., Depledge, M., Wallace, R. and Melzer, D. “Association of urinary bisphenol a concentration with medical disorders and laboratory abnormalities in adults”, JAMA. 300(11), 2008.
[16] Anonyms (Waste Management World). “Landfilled Plastics could power 5.2 million U.S. households”, Waste to Energy: Waste Management World, 2011.
[17] Li, C., Zhuang, H., Hsieh, L., Lee, W. and M. Tsao. “PAH emission from the incineration of the plastic wastes”, Environmental International. 27(1). p. 61-67, 2001.
[18] Lea, W. “Plastics incineration versus recycling: a comparison of energy and landfill cost saving”, Journal of Hazardous Materials. 47(1). p. 295-302, 1996.
[19] Siddiqui, M. and Redhwi, H. “Catalytic co-processing of waste plastics and petroleum residue into liquid fuel oils”, Journal of Analytical and Advanced Pyrolysis. 86(1), 2006.

[20] Williams, P. and Slaney, E. "Analysis of products from the pyrolysis and liquefaction of single plastics and waste plastics mixture", Resource Conservation and Recycling. 51(4). p. 754-769, 2007.
[21] Vali, V., Gnanavel, G., Thirumarimurugan, M. and Kannadasan, T. "Alternate Fuel from Synthetic Plastic Waste", International Journal of Pharmaceutical and Chemical Sciences. 1(3), p. 1069-1073, 2012.
[22] Zadgaonkar, U. and Zadgaonkar, A. "A catalyst composition for catalytic cracking of waste plastic", WO2005094990A1. October 13, 2005.
[23] Baker, G. "Process for conversion of waste material to liquid fuel", EP1577366A2. September 21, 2005.
[24] Bennett, G. "Feedstock Recycling and Pyrolysis of Waste Plastics", Journal of Hazardous Materials. 147(1). p. 682-683, 2007.
[25] Scheirs, J. "Overview of Commercial Pyrolysis Processes for Waste Plastics", John Wiely and Sons, 2006.
[26] Serrano, D., Augado, J. and Escola, J. "Developing Advanced Catalysts for the Conversion of Polyolefinic Waste Plastics into Fuels and Chemicals", Journal of American Chemical Society. Vol 2(9). p. 1924-1941, 2012.
[27] Sriningsih, W., Saerodji, M., Trisunaryanti, W., Triyono, Armunanto, R. and Falah I. "Fuel Production from LDPE Plastic Waste over Natural Zeolite Supported Ni, Ni-Mo, Co and Co-Mo Metals", International Conference of Sustainable Future and Human Security, 2014.
[28] Hazrat, M., Rasul, M., Khan, M., Azad, A. and Bhuiya, M. "Utilization of polymer wastes as transport fuel resources- A recent development", International Conference on Applied Energy. 61(2014). p. 1681-1685, 2014.
[29] Uemichi, Y., Nakamura, J., Itoh, T., Sugioka, M., Garforth, A. and Dwayer, J. "Conversion of Polyethylene into gasoline-range fuels by two-stage catalytic degradation using silica-alumina and HZSM-5 zeolite", Industrial Engineering Chemistry Research. 38(2), 1999.
[30] Cletus, C., Thomas, S., and Varghese, S. "Synthesis of Petroleum-Based Fuel from Waste Plastics and Performance Analysis in a CI Engine", Journal of Energy, 2013.
[31] Akpanudoh, N., Gobin, K. and Manos, G. "Catalytic degradation of plastics waste to liquid fuel over commercial cracking catalysis: Effect of polymer to catalyst ratio/acidity content", Journal of Molecular Catalysis. Vol 235(1). p. 67-73, 2005.
[32] Lin, Y. and Sharratt, P. "Catalytic Conversion of Polyolefins to Chemical and Fuel over Various Cracking Catalyst", Energy and Fuel. 12(4). p. 767-774, 1998.
[33] Park, D., Hwang, E., Kim, J., Choi, J., Kim, Y., and Woo, H. "Catalytic degradation of polyethylene over solid acid catalysts", Polymer Degradation and Stability. 65(2). p. 193-198, 1999.
[34] Shah, J., Jan, M., Mabood, F. and Jabeen, F. "Catalytic pyrolysis of LDPE leads to valuable resource recovery and reduction of waste problems", Energy Conversion and Management. 51(12). p. 2791-2801, 2010.
[35] Tang, C., Wang, Y., Zhou, Q. and Zheng, L. "Catalytic effect of Al-Zn composite catalyst on the degradation of PVC-containing polymer mixtures into pyrolysis oil", Polymer Degradation and Stability. 81(1). p. 89-94, 2003.
[36] Aboulkas, A., El-Harfi, K. and El-Bouadili, A. "Thermal degradation behavior of polyethylene and polypropylene. Part I: Pyrolysis kinetics and mechanism", Energy Conversion and Management. 51(7). p. 1363-1369, 2010.
[37] Sarker, M. and Rashid, M. "Production of Valuable Hydrocarbons by Catalytic Degradation of a Mixture of Polyvinyl Chloride and Polystyrene Waste", International Journal of Engineering and Technology Research. 1(1). p. 39-48, 2013.
[38] Rashid, M. and Sarker, M. "Liquid Fuels and Chemicals from Several Plastic Wastes and Motor Vehicle Tire Mixture by Catalytic Cracking", American Journal of Environment, Energy and Power Research. 1(6). p. 108-116, 2013.
[39] Hazrat, M., Rasul, M. and Khan, M. "A Study on Thermo-Catalytic Degradation for Production of Clean Transport Fuel and Reducing Plastic Wastes", International Conference on Thermal Engineering. 105(2015). p. 865-876, 2015.
[40] Mani, M., Subash, C. and Nagarajan, G. "Performance Emission and Combustion Characteristics of a DI Diesel Engine Using Waste Plastic Oil", Journal of Applied Thermal Engineering. 29(13), p. 2738-2744, 2013.