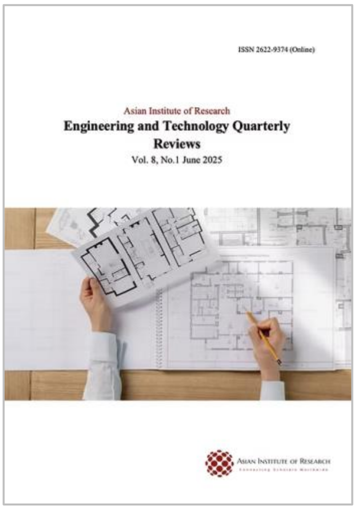

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Pyrolysis as a Process Towards Better Management of Sustainable Recycling of Plastic Waste in Afghanistan: An Overview

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Abstract
The increasing prevalence of plastics and the weakness in the current management of plastic waste in major cities of Afghanistan have been the premise of various studies that have been conducted in the past to some extent with the aim of finding a sustainable solution to this issue. Among the various proposed solutions, chemical recycling and thermal decomposition of plastic waste have not yet been considered. While the pyrolysis process is a promising and suitable alternative for the disposal of plastic waste to traditional methods. The main focus of this paper is to review recent studies on plastic pyrolysis and propose pyrolysis technology as a method based on an engineering perspective toward sustainable development. A systematic review and analysis of the literature focused on chemical recycling and pyrolysis using Boolean logic and Scopus search function. In particular, this paper covers the current status of plastic waste management and identifies pyrolysis technology as an effective process in relation to progress towards sustainable development for Afghanistan. The pyrolysis process, as an alternative to traditional waste management methods of the past, offers specific cases for the application of the pyrolysis process as a new experience in plastic waste management.

Keywords: Plastic Waste, Pyrolysis, Incineration, Afghanistan, Liquid Fuel, Plastic Pollution

1. Introduction

1.1. propose of the review

The propose of this paper is to critically review the current situation and anomalies caused by plastic waste in Afghanistan and well suggest the chemical recycling of plastic as a solution to this problem. Of course, chemical recycling is divers, in this study, I will examine the pyrolysis as an effective chemical recycling method for the better management of plastic waste in the cities and the risks it poses.

When we look at our daily lives, probably one of the most widely used things we come into contact with more various types of plastic. The group of widely used materials has a wide variety of applications in human life. Because plastic is produced in different compositions, shapes and colors (poshan plastic co, 2024). Due to the widespread use of plastic in the last few decades, today this group of unnatural material is considered a major part of human life, so much so that life without it is practically impossible. The widespread use of this material is due to its properties such as light weight, cheapness, easiness of fabrication by heating and molding, insolubility in water, long durability and corrosion resistance (Mourshid, et al., 2017). But its durability and low biodegradability have caused dissonance, including many environmental pollution and greenhouse gas emissions. Since almost all plastics are non-biodegradable, recycling can play a role in reducing plastic waste. This is crucial, for example to reduce the approximately 8 million tons of plastic waste that enters the ocean each years (Jambeck, 2015). The worldwide production of plastic continues to increase every year with over 390 million tons in 2021, up from its beginning in 1950s (Schade, 2024).

Plastic waste management system (PWMS), as a very important issue that has created many environmental challenges in major cities in developing countries (Nadim et al., 2020). The most common methods for plastic waste management systems in such countries are open dumping and open burning. Similarly to other cities in developing countries Kabul as capital city, Qandahar and Herat as major cities in Afghanistan with high populations, poverty and poor waste recycling management have experienced the most environmental damage in the last two decades. According to national environmental protection agency (NEPA) policy and strategy for sustainable development in Afghanistan, the national waste management policy reported that the current situation concerning waste on the statute of waste and its management across the country is limited (NEPA, 2019). In the policy vision guiding principles all the rules of waste management clearly explained. The national waste management policy was comprehensively designed and signed in 2010. Unfortunately, due to many challenges at government level it's not been implemented, which will require further review.

1.2. Overview of Current situation of plastic waste disposal in Afghanistan

In many Asian countries, the awareness of the so called "plastic pollution epidemic" public and policy perceptions of the associated environmental and potential health risks (Dumbili and Henderson, 2020). Afghanistan, with its geographical location in south Asia and with experience of war for five decades, has suffered economic bankruptcy and poverty. On the other hand, the absence of healthy environmental management with increasing population in its large cities has become increasingly affected by urban population, especially plastic waste. There are many reasons for the increase in plastic waste pollution in Afghanistan. The problem recognition and mean reasons for the increase in plastic wastes as follow:

- Population increase due to poverty, unemployment and preference for a better life in the countries major cities such as capital city Kabul in the last two decades
- Failure to implement plastic waste management policy at national level.
- The absence of 7Rs-rethik, refuse, reuse, reduce, repair, recycle and Rot well foster a paradigm shift encouraging sustainable consumption strategy as an important global method in the national master plan for plastic pollution and debris management (Burah and Kumar, 2024)
- Lack of standardized recycling units and upcycling.
- Lack of social responsibility toward urban life
- Lack of public awareness about the environmental and health risks associated with plastic pollution.
- Absence of policy regarding collective contribution to circular economy
- Import ban of plastics production from higher-income counties such as chines, and other neighboring countries regardless of the global impact of plastic waste trade (Brooks et al., 2018)

Therefore, given the issues mentioned above and more other challenge, the current situation in Afghanistan in terms of plastic pollution as a low-income country has placed it in an abnormal situation in terms of environmental pollution and health risks.

1.3. Existing problem and recognition

According to context of waste management in Afghanistan, the policy focused on the solid waste (clinical waste, hazardous waste and municipal waste), according to this strategy, all three types of waste are significantly associated with a high percentage of plastic waste. Afghanistan listed in the most polluted country in the world (Parviz, 2019). Based on the report of National Environment Protection Agency (NEPA), the residents of Kabul city produce over seven tonnes of plastic waste every day. Only plastic bags make four tone of waste and the remaining are mostly plastic bottles. Besides of these problems, the through hazardous can be seen in the consequences of this mismanagement waste. In fact, based on the report of health effects institute’s state of Global Air, Afghanistan has one of the higher per capita rates of deaths from air pollution in the world (Azad, 2015). Based on 2018 reports 0.6kg/day waste per capita was estimated (Noori, 2017).

At the waste management policy was previously formulated and approved in details by the National Environmental Protection Agency (NEPA) in 2007-2008, the pollution control policy and the environmental and social impact assessment policy were also formulated and implemented in February 2018. However, none of environmental policies in the field of waste management were implemented in practice. This shows that the problem of waste management in Afghanistan is not ambiguous. But fundamental reasons such as the increase in urban population and more waste production, poor and mismanagement in waste control, the lack of new and harmless methods for the waste recycling cycle, especially plastic waste and the indiscriminate use of plastic bags as a norm in society as a cumulative threat to the environment have turned Afghanistan’s major cities, especially Kabul into a garbage dump (Parviz, 2019).

1.4. Current situation of plastic waste disposal

Information on the status of plastic waste recycling and its management across the country is still limited. What is observed in the current situation, the lack of any proper waste management and facilities for this process has made waste disposal a difficult issue every day, huge amounts of waste are improperly collected by municipal workers and simply thrown away in a corner far from the city and on farm. This process, with limited facilities (lack of sufficient garbage bins throughout the city, their failure to empty them on time and their improper use by people), makes it impossible to remove all the waste in the city. Currently garbage collection is done in three ways: first; by municipal workers, second; by private sector that hires people and buy garbage and finally some people collect garbage on their own. However, the proportion waste collected is much lover compared to urban residents and waste generation. More waste is generated in unexpected places every day than before which goes by collectors.

Urban construction, population density, a lack of waste management culture, and changes in people's consumption patterns in the big Cities are among the most main factors contributing to unregulated household waste production, which has led to social risks and problems. The increased plastic waste production, lack of suitable and harmless disposal sites, rising employee costs, lack of a regular household waste collection system, underutilization of modern technology, lack of complete property rights, and the full rule of law in underdeveloped cities have led experts and researchers to work on the economic and efficient use of waste and propose innovative solutions in this regard. A significant portion of municipal solid waste consists of high moisture content and foul-smelling odors, as well as the production of leachate during collection, transportation, and disposal, which present numerous challenges for sustainable development (Hazheer et al., 2023). According to the NEPA of Afghanistan and Municipalities law, waste is collected from the outskirts of a city and then transferred to a designated location.

The lack of a defined method for waste disposal is a major problem in Afghanistan. Since Afghanistan does not have a proper recycling system. The use of landfill has become a common practice in this country for many years. Since landfill are located outside and upstream of Kabul city (Dasht-e-chamtala, Kampany and Gazak) heavy rains can carry the waste back into urban areas with water currents. This process pollutes groundwater and poses serious health risks to the community. It also contaminates agriculture soils, making farming impossible. Mismanagement of plastic waste considering landfilling and incineration of waste and its environmental impacts is schematically shown in figure (1).

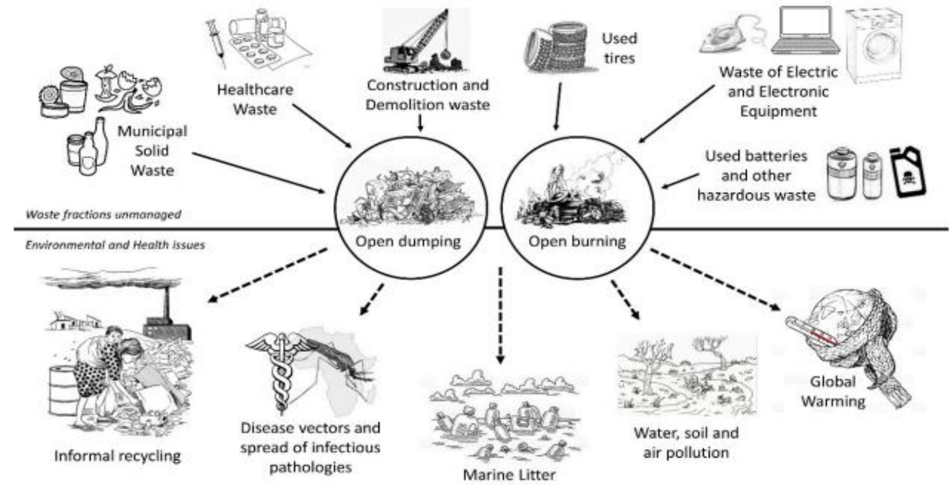


Figure 1: Theoretical framework of the review. Source of plastic waste contamination due to mismanagement *(adopted from Ferronto and Torretta, 2019)*

Open burning of plastic waste is another major challenge in Afghanistan, as is common in other low-income counties. Due to economic poverty, many urbanite burn types of plastic waste and rubber in the winter to heat their homes. Open burning is caused of CO, CO_2, SO, NO, PM_{10} and other pollutant emission that affect the atmosphere (Ferronto and Torretta, 2019). Therefore, mismanagement of solid waste has caused serious and widespread environmental impact that calls into question the process of improving sustainable development.

1.5. Toxic pollutants from plastic waste and human health impact

Municipal Solid Waste contains different percentage in every city in the world. Unfortunately, in Afghanistan major cities it's containing more than 25% of plastic is burnt. As we know, incineration of plastic waste in an open field is a main and significant source of air pollution (verma et al., 2015). Releasing toxic gases such as Dioxins, furan, Mercury and polychlorinated biphenyls into the atmosphere. Releasing of gases due to the type of plastic which is burned, Poly Vinyl chloride liberates hazardous halogens. The release of this toxic substance poses a serious threat health, vegetation and biodiversity in the environment. As a whole, polystyrene has a detrimental effect on the central nervous system. Dioxins accumulate on crops and waterway and enter the body through food. 90 to 95 percent of human exposure to dioxins comes from food, especially meat and dairy products (Nkwachukwu et al., 2013). Dioxins are the lethal persistent organic pollutants (POPs) and the worst component of them tetrachlorodibenzo-p-dioxin known as geotropic, is a to toxic compound that cause cancer and disrupts the nervous system, thyroid, reproductive and respiratory system (Adeniran & Shakantu, 2022).

Three primary routes of exposure to plastic polymers and other polymers additive have been established: inhalation, ingestion and absorption (see figure 1.2).

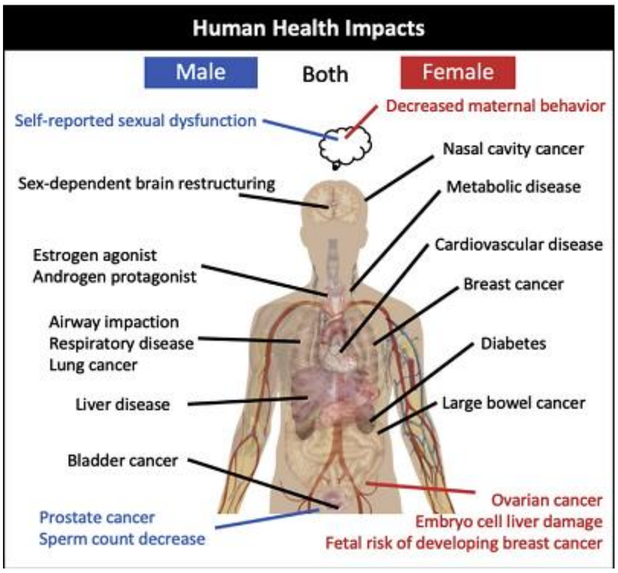


Figure 1.2: Detailed human health impact
(from Cook and Halden, 2020)

Polymer particles that enter the body through inhalation cause respiratory diseases such as nasal cavity cancer, airway obstruction and lung cancer (Cook and Halden, 2020). Ingestion of plastic and plastic polymers through food products may lead to neurological and psychological effects such as: decreased maternal behavior, self-reported sexual dysfunction and sex- dependent brain structuring (Kundakovic et al, 2013). Finally plastic ingestion cause metabolic diseases, bladder cancer and liver disease.

2. Methodology of the review

This is the study and in search of a sustainable solution for disposing of plastic waste disposal, subjected to Afghanistan as a developing country that has endured more than four decades of war, it's in a dire state of climate and environmental change, alongside other anomalies. In the first part of this review paper, the current situation of plastic waste management is presented in order to understand the subject by analyzing relevant publications published in the past decade and present. For wide context the analysis of literature focus on chemical recycling research, as well as analyzing the development of pyrolysis for reuse of plastic material as a sustainable plastic recycling. The analysis was conducted by using Boolean logic and search function of Scopus. The terms were searched for in the title or keyword of published paper between 2015 and 2023. Topics related to this review noted down.

In the second part of this paper a literature search for published chemical recycling methods was completed. This analyzing was not intended to capture all papers relating to the search term used, but to demonstrate general trends in research development over the last 15 years. Additionally the keywords were searched in google scholar to capture any literature not extant in Scopus. Paper selection (chemical recycling, pyrolysis and waste management) with the intention of searching words as follows:

- Chemical recycling (CR)
- Plastic or polymers
- Pyrolysis
- Plastic waste management
- Recycling
- Sustainable development

Of all papers about the chemical recycling and other related words, 9 met all the above criteria.

3. Overview of chemical recycling

Recycling is one of the most appropriate and practical methods of waste treatment, according to waste guidelines in European countries ranks third in the 5-level waste hierarchy (Maisels et al., 2022). Reusing plastic products after processing is definitely conceivable. Reusing plastic production waste (in simple, small cut pieces) in the manufacture of new plastic products is considered primary recycling and one of the best methods for recycling. However, the mechanical recycling (secondary recycling) also has its limitations due to the presence of high contamination in their mixtures and the heterogeneity of plastic products. Here, the chemical recycling process can fill all the gaps in the cycle and be defined as a sustainable and relatively green recycling method.

Research into chemical recycling of plastic wastes has increased over the last decade. At the same time, life cycle assessment (LCA) methodology and application have developed and LCA continue as important tool for understanding the environmental impacts of materials and processes (Davidson et al., 2020). Chemical recycling in the basic sense, the use of thermo and/or chemical techniques to break down plastic waste into monomers, oligomers or at least molecules with a low molecular weight with physical states (liquid, solid and gaseous) hydrocarbon mixes. One of the advantages of chemical recycling is that it results in polymers or other chemical products of the same high quality as new materials. Some of this decomposed products are used in the production of new plastics. However, there are some disadvantage to chemical recycling such as the high amount of energy required to breakdown the polymer chains, because chemical recycling processes produce mixtures that are composed of low molecular weight, relatively low value molecules instead of the specific monomers needed to produce new plastics.

Considering the chemical principles, various processes applicable for decomposition include hydrolysis, solvolysis, hydrocracking, catalytic cracking, pyrolysis and gasification. Each of this processes can be of importance in the management of plastic waste. Incineration is also a chemical process, in which the combustion products (CO_2, H_2O) are not recycled. Therefore, this process cannot be considered as recycling (Misels et al., 2020). When the chemical recycling of plastics from WEEE is reported, it is usually identified as feedstock recycling, including only thermal and catalytic pyrolysis together with hydrothermal treatment (Achilias et al., 2024).

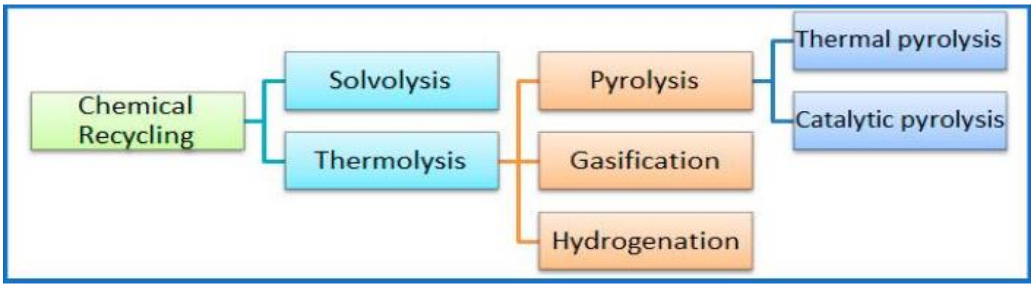


Figure 3: Chemical recycling methods of plastic wastes from WEEE
[Adopted from Achilias et al., 2024.]

In the following section, as a fundamental objective of this study, I will examine the chemical recycling process of pyrolysis, as an important opportunity to reduce plastic pollution and contribute to the country economic cycle and as a sustainable process. The outcome of this study can have a batter perspective for better management of plastic waste (MPW) in Afghanistan. This method of recycling may have been experienced in the past in Afghanistan, but today's serious challenge caused by plastic waste requires modern solutions to remove our society towards a green future free from the environmental and health issues of plastics.

4. An overview of the pyrolysis process

Among all the chemical recycling processes for plastics, pyrolysis is a thermochemical process that takes place in the absence of oxygen. This method can be carried out at low temperatures below 400 C° and at high temperatures of 700 C° (Schade et al., 2024). In this thermal interval, plastics can be converted into petrochemical feedstock's such as naphta, liquid and waxy hydrocarbons (olefins, paraphins, naphtenes and arolatics), and synthesis gases ($CO_2 + H_2$). The products obtained in the pyrolysis process depends on parameters such as temperature, composition and type of plastic waste and the use of catalysts in the process. For example, deferent types of plastic wastes such as HDPE, LDPE, PET, PP and PS used as a source of carbon for generating carbon nanotubes (CNTs) using different stage processes. In the first stage, plastic waste is thermally cracked at 700 C° to produce hydrocarbon gases. In the other stage, the decomposition of developed gases is carried out at 650 C° to form CNTs and H_2 gas by using the $Ni\text{-}Mo/Al_2O_3$ catalyst (Aboul-Enein, et al., 2018). As we can see in figure (3), pyrolysis products (gases, liquid, char and residue) are usually formed by thermal breakdown of plastic waste. As we can see, the efficiency of the pyrolysis process depends mostly on the type of plastics waste.

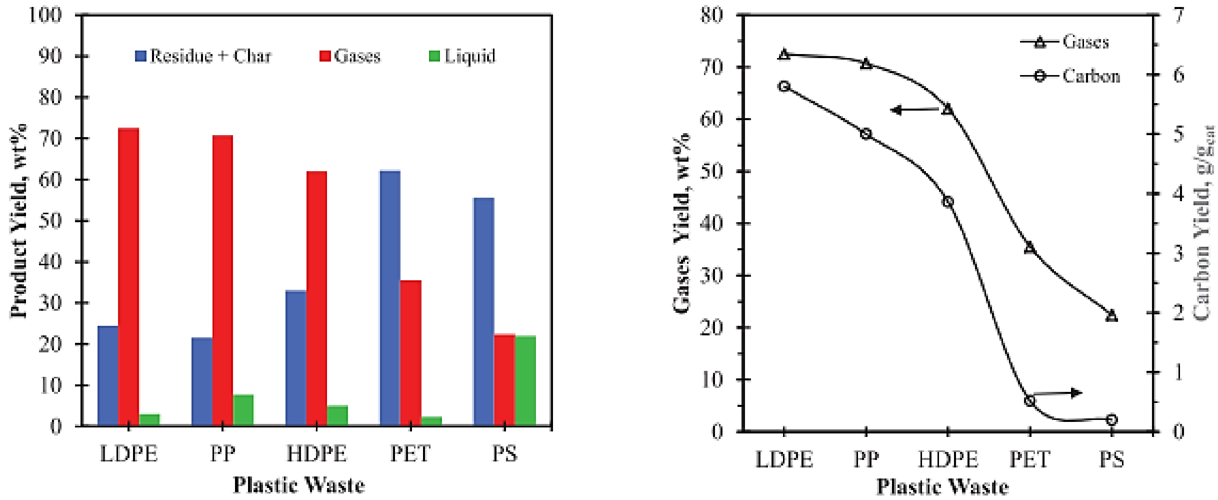


Figure 4: (left) type of production efficiencies in pyrolysis considering the type of plastic waste, (right) effects of plastic waste type on the yield of gases and carbon products

(Adopted from Aboul-Enein, et al, 2018)

The mechanism of chemical recycling of polymers through pyrolysis involves heating polymers at high temperatures in the absence of oxygen, which results in their decomposition into smaller molecular fragments. The following is a simple explanation of the general steps of the pyrolysis process for polymer recycling:

- **Heating**: Plastic wastes is heated in a controlled, oxygen-free environment to high temperatures, usually between 400C° - 800 C°. This is usually done in specialized pyrolysis reactors.
- **Thermal decomposition**: As the temperature increases, the supplied heat energy breaks the chemical bonds that hold the polymer chains together, and the polymer chains within the material begin to break down through a process called thermal decomposition or cracking.
- **Condensation**: The evaporated polymer particles are rapidly cooled and condensed to form various products. The condensation process can be controlled to obtain specific fractions such as gas, liquid fuel, or waxy solids. The final product of the pyrolysis plant is fuel oil, carbon black, and petroleum gas.
- **Collection and Separation**: The concentrated products are collected and separated based on their physical properties and composition. Distillation and other separation techniques are commonly used to separate the different fractions. The separated fractions, such as liquid oils or waxy solids, may undergo additional processing steps such as purification to obtain products or feed-stocks that can be used for various applications.

It is important to note that the pyrolysis process can be affected by factors such as the type of polymer, pyrolysis conditions (temperature, time, catalyst, etc.). Therefore, the specific mechanisms and conditions may vary depending on the polymer being recycled and the desired output. The figure below shows a schematic of this process.

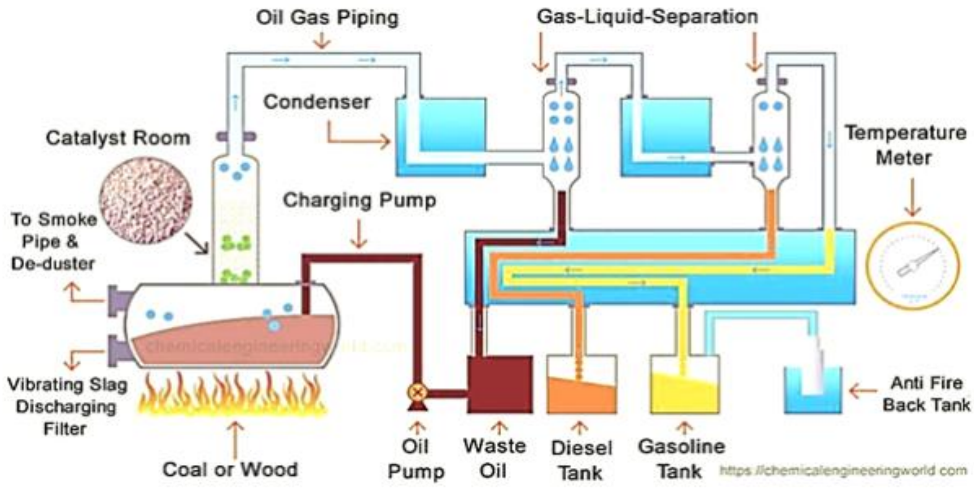


Figure 5: Schematic show of pyrolysis process with deferent steps
(from https://www.atmanpolymer.com/).

4.1. Types of waste treated with pyrolysis

Depending on raw material and collected plastic wastes for pyrolysis process, the composition of paralytic products can be significantly different. Three examples of products are formed from thermal decomposition in this process according to the parameters of pyrolysis, which are shown in Table (1).

Table 1: Products allocation of pyrolysis with three different wastes.

feedstock	**reactor**	**Temperature(C°)**	**Yield (Wt%)**		
			gas	**Liquid**	**solid**
Tires	Moving screw bed	600	11.7	48.4	39.9
plastics	Semi-batch reactor	500	34.0	65.2	0.8
Biomass and plastic	Autoclave	400	∼9	∼65	∼17

[Adopted from Czajczyńska et al, 2017.]

4.2. Thermal pyrolysis of plastics

Thermal pyrolysis a simple and a novel technology for plastic waste management in European and some of the Asian developing countries. This process is in fact an economic solution that guides waste management, especially plastic waste, towards sustainable development (Xayachak et al., 2022). The products obtained from this thermal process of plastics include (i) carbonized coal (ii) non-compressible gas and short-chain hydrocarbons (iii) condensable gas/vapor which forms the liquid fraction of the product stream and contains heavy oil (diesel), oil (gasoline), crude oil (naphtha) and wax.

4.3. Effects of feedstock decomposition and different types of polymers

Different types of polymers have unique behaviors during the pyrolysis process. To present this discussion comprehensively, we briefly review the types of common plastics that account for the largest percentage of waste (Table 2).

4.3.1. High density polyethylene (HDPE) and low density polyethylene (LDPE)

Polyolefin (PO) which includes polypropylene (PP), High density polyethylene (HDPE) and low density polyethylene (LDPE) was the largest component of waste plastic, and made up 15.5% of the global plastic production in 2019. HDPE can be characterized as a long linear polymer chain with a high degree of crystallinity and low branching which leads to high strength properties. In contrast, LDPE has more branching that results in weaker intermolecular forces, thus lower tensile strength and hardness. However, LDPE has better ductility and it is easier to mold (Czajczyn´ska et al., 2019). HDPE polymers are resistant to many solvents and have a wide variety of applications: bottle caps, food storage containers, plastic bags, backpacking frames, banners, folding chairs and tables, fuel tanks for vehicles, piping, storage sheds, 3-D printer filaments and many more. LDPE is widely used for manufacturing various containers, dispensing bottles, wash bottles, packaging foam etc. Plastic bags are the most popular use of LDPE.

In contrast with, these types of polymers are highly appropriate for pyrolysis, which demonstrates the complementarity of mechanical and other chemical recycling technologies. Additionally, carbon content in (PO) can range from 83.7 to 86.1 wt. % (Xayachak et al, 2029). The high carbon content in PO translates to oil with elevated higher heating values (HHVs)

4.3.2. Polyvinyl Chloride (PVC)

PVC is one of the most important products of the chemical industry and it is a widely used plastic. From 2022-2020 annually more than 3 million tons of (PVC) were imported for application in buildings and construction specially to make gateway and windows from neighboring countries to Afghanistan. Other applications for PVC are pipes and fittings, profiles and tubes, rigid film and sheet, cables and bottles. This polymer is linear and strong and it is produced by the polymerization of the vinyl chloride monomer. PVC consists of 57% of chlorine and 43% of carbon. Due to the high chlorine concentration, during the pyrolysis of PVC highly toxic HCl (Hydrogen chloride) releases and can pose a threat to the environment and humans. This compound is very corrosive and can damage the pyrolysis installation. Furthermore, direct pyrolysis without chlorine removal can instigate the production of hazardous chlorinated hydrocarbons, such as polychlorinated dibenzodioxins (PCDD), dibenzofurans (PCDF) and polychlorobiphenyl (BCP).

Different methods have been proposed to remove chlorine from PVC feedstocks, including stepwise pyrolysis, metal sorbents, hydrothermal treatment, catalytic pyrolysis and chemical removers (Cook et al., 2020). Stepwise pyrolysis is the most common approach and involves an initial stage where PVC feedstock is heated to moderate temperatures (≈330 °C), which provides sufficient energy to cleave carbon-chlorine bonds, but not carbon-carbon bonds. Once chlorine has been volatilized, the main polymeric chain can be formally pyrolysis in secondary reactor and novel extruder (Xayachak et al, 2022).

4.3.3. Polystyrene

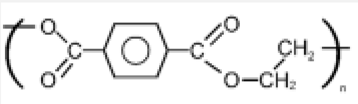
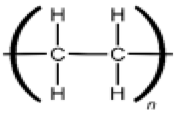
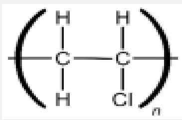
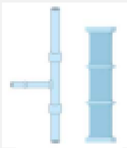
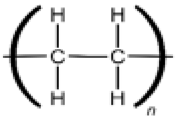
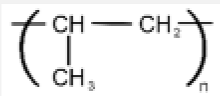
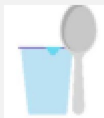
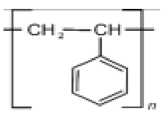
Polystyrene is a synthetic aromatic polymer in which a benzene ring is attached to each substituted carbon in the chain and is formed from styrene monomers. This polymer is available in solid or foamed products. It has wide applications in various sectors such as construction, protective packaging of electrical appliances, toys, etc. Unfortunately, pyrolysis poses a serious threat to the environment, as this plastic is non-degradable. It poses serious risks to biodiversity because animals cannot recognize polystyrene foams as a synthetic material and consume them. This polymer has negative effects on birds and other marine animals. The degradation of polystyrene is through the termination of the chain, resulting in the formation of styrene monomers, which are separated from the main chain. Styrene monomers are obtained in the form of crude oil and are used to produce other high-quality plastics.

Achilias et al (2024) investigated the pyrolysis of raw polystyrene and plastic glasses and plastic containers also made of polystyrene. They obtained 91.8 wt% of liquid and 2.5 wt% of gas at 510 C˚ from model polystyrene in a bench scale fixed bed reactor. Styrene (63.9 wt% of liquid) and 2, 4-dipenyl-1-butene (14 wt%) were predominant components of the liquid with smaller amounts of toluene, a-methylstyrene, 1,2-diphenylethane and some extra compounds. Gases consisted mainly of ethane, methane, propylene and pentane-pentane. The residue was 5.7 wt%. Compared to model polystyrene, real styrene products formed a lower amount of the liquid fraction. On the other hand, thermal cracking of polystyrene at 450 C° produced 84 wt% of liquid, 13 wt% of gas and 3 wt% of char (Czajczyńska et al., 2017).

4.3.4. Polyethylene Terephthalate (PET)

Polyethylene Terephthalate (PET) has become the preferable choice for plastic packaging for food products, beverages such as mineral water and other soft drinks, sheets, trays, different bottles. This is due to its inherent properties that are very suitable for large-capacity, lightweight and pressure resistant containers. Also ET widely used as prepaid cards, fibers, films (Eze, et al., 2021). PET has become one of the most popular plastic in daily human life and it’s often recycled with various methods of chemical recycling. For easy recycling process, the PET wastes should be divided according to different colors. PET is not a desirable component for plastic pyrolysis process due to the presence of Oxygen in the polymeric chain, because during the pyrolysis some of the water and undesirable oxygenated compounds produced. Additionally, pyrolysis of PET does not produce fluid oil, but a ductile substance that is difficult to handle (Sogancioglu et al., 2017). Furthermore, pyrolysis of PET forms benzoic acid, which can block pipes and reduce the quality of pyrolytic products.

Table 2: An overview of common plastic types and their pyrolytic products (Xayachak et al., 2022).

Plastic Name(SPI cod)	Chemical structure	Degradation (C°)	Primary products	applications	Sample
PET (1)		>300	Benzoic acid; formaldehyde; benzene; toluene, short aliphatic	Sheets,films, plastic bottles and food trays	
HDPE (2)		>400	Paraffinic waxes;	Milk and shampoo bottles; detergent containers	
PVC (3)		250-350 Dichloronation	Aromatic; HCl; coke.	Pipes; electrical wiring insulation and wall covering	
LDPE (4)		>400	Paraffinic waxes; α-olefin	Ziploc bags; plastic bags; cling wraps and agriculture films	
PP (5)		>370	Short chain alkenes and alkanes; olefin	Food packaging; microwave- safe containers	
PS (6)		>300	BTEX styrene monomer	Styrofoam, plastic utensils, building insulation and packaging	

Pyrolysis for plastic waste management, apart from being an engineering vision, is considered an effective method of chemical recycling. Pyrolysis and its latest developments, various conditions of evaluating the application of this process in the waste management and waste treatment sector are of great importance. In particular, the type of residues and their use are of great interest because they can be an important source of secondary raw materials or have a beneficial effect in the treatment of plastic waste (Czajczyńska et al., 2017).

4.4. Pyrolysis products and their applications

The pyrolysis process in plastic recycling has the ability to convert heterogeneous materials. This process is used for plastic waste that is not amenable to mechanical recycling. Other additives and contaminants in collected plastic waste, such as metals or flame retardants, are purified and separated into a coke- like matrix in solid or residue form after the process. These ashes may contain noxious substance which require further treatment or disposal. In general, the products obtained from pyrolysis require further processing, such as distillation. Sometimes these products have high value. The resulting liquids may sometimes contain sulfur, which is a critical value. Because sulfur reduces the conversion capacity of catalysts in automotive fuel and leads to increased nitrogen oxides (N2), carbon monoxide (CO), hydrocarbons, and volatile organic compounds (VOCs).

Although pyrolysis products have a lower calorific value than other conventional fuels, pyrolysis oil is a popular source of interesting biochemical and renewable compounds on the market. In general, the oil obtained from the waste pyrolysis process requires further processing to ensure its stability and compatibility with existing petroleum-based fuels. By using different feedstock's and clean biomass pyrolysis processes, valuable and high-quality oils can be produced that are used as food flavorings, plant preservatives, or growth promoters.

Usually, the thermal decomposition of waste is carried out for the purpose of energy recovery. Most of the products have the properties of fuel sources. Since pyrolysis allows the conversion of waste into energy sources, pyrolysis products are extremely important for energy supply purposes and contributing to the economic process. Examples of these products are as follows:

4.4.1. Pyrolytic oil

Pyrolytic oil offers more opportunities for use than pyrolytic gas. The product may differ substantially depending on the composition of the raw materials and the mechanism of pyrolysis upon heating (Czajczyn´ ska et al., 2017). Oils produced by heating biomass have the potential to be used as an alternative fuel to fossil fuels. This product must be upgraded by pyrolysis because it contains high levels of oxygen, which reduces the calorific value (Abnisa et al., 2014). Pyrolytic oils derived from biomass are mainly composed of compounds such as acids, sugars, alcohols, aldehydes, phenols and their derivatives, furans and mixtures of oxygenated compounds. Phenolic compounds are mostly in high concentration (up to 50 Wt %) which include relative amounts of phenol, eugenol, cresol and xylinol and higher amounts of alkylated (poly-) phenols. These products can be used as producers of heat, electricity, syngas or other chemicals. At temperatures between 500-600 C° the highest oil yield is achieved, when biomass is processed with heat values of around 15-20 MJ/Kg. Pyrolytic oil from plastics has a higher heat value of around 30-45 MJ/kg.

4.4.2. pyrolytic gas

In general, it is possible to say that the composition of pyrolytic gas is strongly dependent on the pyrolysis temperature and the type of waste involved. Slow pyrolysis of biomass wastes such as wood, garden waste and food residues at low temperatures (less than 400 °C) produces a smaller amount of gas, which consists of CO2, CO and light hydrocarbons (Czajczyn´ska, et al., 2017). Pyrolysis of plastics produces a gas whose main components are light hydrogen hydrocarbons such as methane, ethane, propane, propene, and butane. Pyrolytic gas has a significant calorific value, for example, the calorific value of PP and PE gas is 42-50 MJ/kg in variation. The pyrogas from MSW consist of CO2, CO, hydrogen, methane and other light hydrocarbons with an average heating value of around 15 MJ/Nm^3, which increases with increasing temperature (Hwang et al., 2014). The most suitable demand for pyrogas is its use as a source of the energy required for the pyrolysis process itself.

4.4.3. pyrolytic char

Another type of pyrolysis product is a solid fraction, called pyrolytic char. Char is essentially composed of a carbon-rich matrix with inorganic by-products. The calorific value of char obtained from co-pyrolysis of waste (mixture of biodegradable and non-biodegradable) is approximately 34 MJ/kg. Char is particularly comparable to coal. However, as expected, some heavy metals or some hazardous elements such as Cl, S, and N remain as solid products. Characterization of their properties is important for the environment and humans. In general, it is a combustible product that can be used to provide energy for the pyrolysis process or for other purposes. The char obtained in pyrolysis is not only a suitable fuel, but can also be processed into activated carbon. The possible applications of char have been further reviewed by Zeng et al.

5. Advantage of using pyrolysis in plastic waste management

Liquid fuel obtained from plastic waste is heavier than conventional commercial fuels and therefore has a higher calorific value, slightly less than or greater than 1000kcal/L. This advantage can increase its application in boilers, cement plants, steel plants and glass factories (Khan et al., 2016). As a feed selectivity, the pyrolysis process is suitable for all types of plastic waste and most common plastics, clean or unwashed and unclassified, and does not require the process of sorting or crushing the waste. The entire process, from the beginning of plastic waste to fuel production, is carried out inside the waste pyrolysis reactor along with its auxiliary system, very convenient and man-power saving. Co-pyrolysis of plastics with waste paper biomass (Supramono, 2018) and even plastics from medical wastes (Biden, 2018) has also been reported.

The technical opportunities in the pyrolysis process are more, which are briefly explained here as follows:

1- Quality of feedstock
Since plastic waste is classified into two general categories: post-industrial and post-consumer, the characteristics of these waste streams are different from each other. Post-industrial plastic waste is clean, but collected plastic waste is usually dirty and contaminated with various types of foreign materials such as glass and wood fragments, metals, etc. This makes post-consumer waste not ideal for mechanical recycling; unless it is completely clean and free of any heterogeneous materials. Because heterogeneous waste is more likely to be incinerated or landfilled. Plastics gradually degrade over time. This process is caused by a variety of factors such as water, air, light, and thermal stresses (cold and hot), chemical and biological conditions, and contact with various materials. In most cases, their degradation makes their properties unsuitable for recycling; in some cases, they are not even suitable for mechanical recycling. The thermal decomposition process or pyrolysis process allows such plastic waste to be converted into valuable fuel oil/monomers (Oasma et al., 2020).

2- Simplicity of the process
Pyrolysis process has been developed as an important thermal process in plastic recycling over time, to convert organic materials and polymers into valuable liquid fuels. Much research has been done in this field to meet the changing needs and challenges in this process. For example, the design of new reactors has been optimized according to the recycling requirements, while at the same time efforts have been made to use valuable catalysts for organic yield and to minimize energy consumption. Pyrolysis is a relatively simple process, which is capable of treating a variety of plastic wastes. These wastes range from packaging waste to more complex materials such as rubber and plastics from WEEE (waste electrical and electronic equipment), hospital waste which are contaminated with toxic and hazardous substances. Therefore, pyrolysis is a mature process that plays an extremely active role for commercial biomass and plastic factories.

3- Infrastructure
No need for additional infrastructure Pyrolysis technology does not require large infrastructure, it can be installed in small environments and mobile units. It is possible that raw materials will be more accessible and convenient in waste collection areas. This approach eliminates the cost of transporting waste to a centralized recycling unit, which also reduces the carbon footprint of the value chain.

4- Self sustainability
The pyrolysis process of plastic produces a hydrocarbon-rich gas with a thermal energy of 25-45MJ/kg (Oasmaa et al., 2020). Which is ideal for energy recovery. Therefore, in commercial scale pyrolysis, the energy produced is recycled back into the process to provide the energy required for the process itself. Therefore, the process is self-sustaining overall.

Considering the above, the pyrolysis process has the freedom to adjust the product by changing the type of reactors, the use of catalysts and the operating conditions. This process is very profitable from an economic point of view. Although, in most cases, the yield of pyrolysis liquid is the main goal of the process, the process can be optimized for the production of waxes, monomers, aromatics, or selected chemicals using catalysts. In the field of energy storage, pyrolysis products can be stored as backup power and used when needed. In the field of industrial materials purification, the wax oil obtained from the thermal decomposition of plastics by pyrolysis is rich in hydrocarbons, which can be ideal as feedstock for refineries. Although the scale is currently insignificant compared to crude oil, it is valid in a proven sense. This process shows that thermochemical recycling closes the loop in the circular economy of plastics (Ikäheimo et al., 2019).

6. Pyrolysis as an effective method of plastic recycling in Afghanistan

Since environmental pollution due to improper solid waste management is a global issue, open dumping and open burning are the most common waste disposal methods, mainly seen in low-income countries. Since plastics are non-biodegradable, they cannot easily return to the natural carbon cycle (Ferronato & Torretta, 2019). In Afghanistan, the demand for plastic products has been increasing due to the increasing population. Afghanistan, like other developing countries, has been increasingly using various types of plastics and lacks of effective management in controlling and recycling plastic waste, which has led to the accumulation of waste in large cities and throughout the country. In addition to the unpleasant and unsightly landscape it has created, this issue has caused serious problems in the country's health and environmental sectors. The methods that have been common in the past or now for collecting and disposing of waste in this country have been incineration and landfilling. Sometimes, mechanical recycling of polymers does not seem to be a suitable and good method for reducing polymer disposal due to their diversity and the problems of their initial separation; for this reason, the development of chemical recycling methods has received more attention today.

In recent years, studies have been conducted on addressing the challenge of urban plastic waste and better waste management in the form of case studies for major Afghan cities such as Kabul, Herat, and Kandahar. Scenarios and suggestions for better waste management have been made. Also, the necessary incentives at the government level for better management of urban waste and its recycling methods have always existed. With the establishment of the National Environmental Protection Agency, laws, regulations, procedures, and bills have been widely presented. However, the fundamental challenges, as presented in the introduction section, have not yet been able to control the challenges of urban plastic waste management.

The research findings and recommendations for better urban waste management have focused on (1) improving the design of municipal facilities and increasing the number of garbage bins in cities, hiring more staff, hiring assessment teams, implementing modern technology, and improving the research process in this field (Mangal et al., 2023). (2) Research findings sometimes point to social issues and present social performance in the waste management system, for example, a poverty-stricken community as a scenario. In this regard, integrating informal workers into a formal framework, strengthening waste recycling, sanitary and unsanitary waste disposal processes, and choosing a suitable location for landfills are considered social issues (Azimi et al., 2020). Studies on plastic waste management in most Asian countries show that plastic waste has increased by 12-30% over the past decades. Afghanistan is no exception to this trend. While several governments have taken steps in this area, improving laws, regulations and strategies on plastic waste as management tools, developing alternative plastic waste solutions, implementing the 7Rs policy (Reuse, Reduce, Restore, Rethink, Recycle, Replace and Refuse), Ban on plastic bags, increase tax on plastic materials, Pfand and promoting education on environmental protection through environmental organizations have been implemented in the last 20 years (Marnn et al., 2020). However, the lack of financial incentives and support for recycling plastic waste has meant that there has been little incentive or legislation to use recycled plastics as raw materials. The challenge of poor management in plastic recycling is almost stagnant. Therefore, in this study, considering the above, chemical recycling of plastic waste (thermochemistry, pyrolysis) is briefly introduced as a new and effective technology and proposed for sustainable environmental development in Afghanistan.

Chemical recycling supports mechanical recycling by recycling plastic waste that is not mechanically recycled. Pyrolysis, as the most researched recycling method, is the most common chemical recycling method that LCA has been modeled using. Pyrolysis is often highlighted as the best chemical recycling method (Davidson et al., 2021). Since pyrolysis is one of the available technologies for converting plastic waste into an intermediate liquid product that can be converted into hydrocarbon biofuels. The pyrolysis plant has a flexible design, designed to recycle various types of organic polymeric materials and waste plastics. Various products such as diesel, gas and carbon black, oil are produced and create new sources of energy and alternative fuels. In fact, pyrolysis products are used as liquid fuels in other industries. Carbon black can be used in the production of car tires, paints and inks. The gases produced from pyrolysis are used as energy sources, the pyrolysis plant effectively uses its produced energy to drive the process and minimizes the use of renewable energy. The temperature and pressure inside the plant are automatically controlled. This process can help manage plastic waste in Afghanistan and create an economy-oriented management.

Since most plastic polymers take hundreds of years to decompose, or remain in the environment in the form of macroplastic particles (Schade et al., 2024). Considering this global problem, examining the situation for a country like Afghanistan shows that with the annual production of millions of tons of plastic waste in the country's large cities and the weakness in waste management and recycling, the process of sustainable development will face a major challenge. The question that arises here is: How can the problem of plastic waste disposal be solved? What the world is using today to deal with this problem is careful management, investment and the use of new technologies based on chemical recycling. Today, Afghanistan, as a war-torn and poor country, has been faced with the problem of waste disposal, and the potential dangers arising from environmental pollution cause the death of hundreds of people in this land every year. Therefore, here we prioritize pyrolysis technology as an effective process in the chemical recycling of polymers as an effective method and in conjunction with progress towards sustainable development for Afghanistan, and we propose the following for its implementation:

1- The pyrolysis process, as a globally accepted method for recycling polymers, should first be studied and researched as a principle in environmental protection through the country's scientific institutions in accordance with the environmental situation in Afghanistan. This process should be included in the curriculum of the environmental engineering department and its specialists should be trained using its scientific method.
2- The government should design a policy considering the environmental protection laws so that the relevant departments can work together in the field of plastic waste recycling and management. These departments include (Environmental Protection Department, Municipality, Ministry of Refugees, Urban Development, Trade, Energy and Water, Petroleum, Agriculture, Higher Education and Education).
3- In order to cover the initial costs of purchasing pyrolysis technology reactors and installation, the government should take action by following the example of regional and neighboring countries in accordance with the country's needs.
4- Encouraging and encouraging the private sector to implement this process is an effective and economy-oriented step. Because on the one hand, market competition has been created, and on the other hand, pyrolysis products add to their capital.
5- By promoting the pyrolysis process, mechanical recycling of plastics will also grow. Because in the mechanical recovery of plastics, a basis for the production of raw materials for lithium-ion batteries, metals, etc. will be created. There will be methodical competition in the private sector.
6- Each pyrolysis device has the status of a manufacturing plant. Although the people of Afghanistan are in conditions of poverty and unemployment, therefore, a large number of people will have jobs and will solve the problem of poverty and unemployment to some extent.
7- There are several indicators of the relationship between poverty, income and environmental degradation. World Bank research has also shown that in low-income countries there is a negative and significant relationship between income and environmental performance index. From this point of view, most urban families in Afghanistan, due to their poverty and lack of clean fuels to heat their homes in the winter, are forced to burn polymeric materials (types of plastic and worn-out car tires). Therefore, the pyrolysis process, by producing liquid fuel sources and supplying them to the market at a reasonable price, or by replacing collected waste with pyrolysis products in pyrolysis centers, will be suitable for better management of plastic waste.

7. Conclusion and suggestions

The world is facing the problem of plastic waste pollution more seriously than ever before. With the increase in global plastic production, its recycling rate is at a low level. Although the recycling rate in industrialized and developed countries has increased by about 10- 30%, this trend still shows that compared to global plastic production, more and more plastic ends up in landfills, which poses a serious threat to the ecosystem. Therefore, better options for the end of the life of plastic waste, efforts to support and develop them are considered essential. In Afghanistan big cities especially Kabul are densely populated and one of the most unorganized cities. Currently, all most all cities are practicing the same process for managing waste.

Large amounts of plastic waste are produced in this country. Proper management of this waste is a serious necessity to protect the environment from hazardous effects. However, lack of facilities, population growth, non-standard infrastructure development, insufficient budget, poor management and lack of coordination of government sectors in environmental protection hinder management. In addition, traditional waste management methods such as composting, landfilling and incineration are obsolete and are not very effective in managing plastic waste in this country and cause further pollution of air, soil and groundwater. Therefore, modern, effective, economical, easy and sustainable strategies and solutions must be sought and experienced. The discovery of methods for chemical recycling of polymers at moderate temperatures and the use of catalysts, with high selectivity, is currently applicable as an alternative method for recycling waste.

Pyrolysis is a suitable alternative to combustion, incineration and landfilling. This emerging technology is in line with the development goals of environmental protection and sustainable development. As a chemical process that breaks down plastics into their raw materials. The key products of this process are crude oil-like liquids that are suitable as fuels in many chemical processes, energy requirements of homes, pyrolysis plants and other engineering applications, enabling a closed-loop process. Pyrolysis is a comprehensive plan for the circular economy and environmental design, providing ready-to-use fuels in an easy and safe way. In addition, the increasing amounts of plastic waste and the increasing fraction of thermoset plastics further highlight the importance of pyrolysis.

As reported in this article about the pyrolysis process as an alternative to traditional methods of plastic waste management in Afghanistan, the following are suggested for using the pyrolysis process as a new experiment in plastic waste management:

- More efforts should be made to implement new and next generation technologies that are available on a laboratory scale as industrial and sustainable solutions. Seek new solutions to eliminate the problem of plastic waste disposal in the country as a whole.
- Afghanistan has witnessed decades of instability. The country is still highly vulnerable economically and politically. Many city dwellers do not consider it their duty to keep the country clean due to lack of awareness of the hazardous environmental consequences. Instead of following the 7Rs, they also produce a large amount of waste every day that ends up in landfills or scattered around the city. Therefore, pyrolysis is proposed as a suitable, cheap and cost-effective, economy-oriented technology for environmental protection and sustainable development.
- New design methods can convert large volumes of plastic waste into alternative fossil fuels. The pyrolysis process reduces the risks of plastic waste disposal and reduces the consumption of oil and its derivatives. The use of catalytic chemical decomposition methods is due to high efficiency in developing countries, these industrial and semi-industrial projects should also be used in Afghanistan.
- The pyrolysis process, in addition to producing fuel supplements based on the basic needs of the country, plays an important role in eliminating environmental pollution. Utilizing the pyrolysis process to remove plastic waste from the environment and turn the aforementioned threat into an opportunity is a practical solution. Given the simplicity of the process, it has sufficient economic attractiveness for investment.
- Finally, for a national strategic plan in the field of environmental protection and sustainable development, scientific topics on new methods and processes for recycling plastic waste and other municipal waste should be added to environmental engineering curricula and, according to the needs of environmental engineering, scientific centers should be created to train more specialists.

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