Indonesian Journal of
Chemical Analysis
Homepage: https://journal.uii.ac.id/IJCA

The Role of Zeolite (*Microporous Crystalline Aluminosilicates*) In Catalytic Pyrolysis of Waste High- and Low-Density Polyethylene Bags for Production of Fuel and Chemicals: A Review

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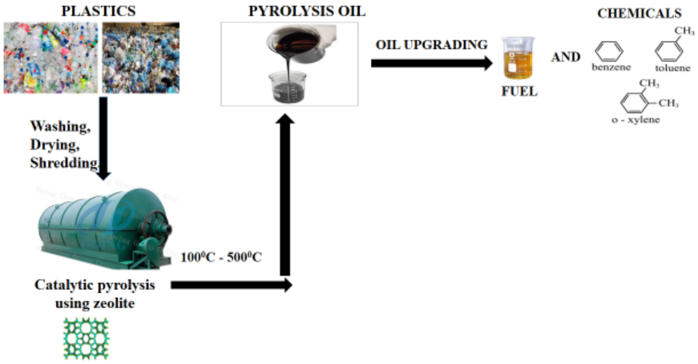
DOI: 10.20885/ijca.vol7.iss1.art9

GRAPHICAL ABSTRACT



ARTICLE INFO

Received : 8 March 2024
Revised : 22 March 2024
Published : 31 March 2024
Keywords : Zeolite, waste polyethylene bags, pyrolysis, fuel Chemicals

ABSTRACT

This review provides a state-of-the-art summary of zeolite's role as a catalyst via pyrolysis to recover fuels and chemicals from waste high and or low-density polyethylene bags. It also highlighted the two types of zeolites (natural or synthetic) used as a two-stage pyrolysis–catalysis in giving a free waxing product to pure fuel and chemicals, which can be subjected to further analysis or upgrading. As yield of oil/wax decreased with the addition of a zeolite as a catalyst from 44 and 58 wt.% (depending on the waste high-density polyethylene "HDPE" or low-density polyethylene bags "LDPE" and other factors). However, the composition of the pyrolysis–catalysis oils significantly increased in aromatic hydrocarbon content accordingly. In addition, the composition of the oils shifted from high molecular weight hydrocarbons (C_{16+}) to fuel range hydrocarbons (C_5–C_{15}), with a high content of single-ring aromatic hydrocarbons such as benzene, toluene, ethylbenzene, xylenes, and styrene. This process shows excellent potential for producing fuels or chemicals and addresses the urgent issue of waste HDPE or LDPE disposal.

1. INTRODUCTION

1.1. High- and low-density polyethylene bags as municipal waste

Plastic bags, sometimes polyethylene bags, are a prominent type of solid waste material in society because of their widespread use and the sluggish pace of disintegration. They also harm human health; they may contain harmful acids, which may lead to death [1]. Because they are inexpensive and convenient, these bags are frequently used for storage, shopping, and shipping. Additional plastics include polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), high-density polyethylene (HDPE), low-density polyethylene (LDPE), and polyethylene terephthalate (PET), among others. However, their sluggish pace of decay and inappropriate disposal have raised environmental issues. According to a study by Jambeck et al., [2] Plastic bags are a significant source of marine waste, endangering ecosystems and aquatic life.

Furthermore, plastic bags (Figure 1) contribute to drainage system obstruction and soil pollution [3,4]. The non-biodegradable nature of polyethylene (plastic in general) further contributes to their persistence in the environment [3,5]. Studies have shown that polyethylene bags can take hundreds of years to decompose, posing a significant threat to ecosystems and wildlife [6]. As a result, they accumulate in landfills, leading to increased solid waste volume and limited space for other waste materials, increased mosquitoes, insects, and bugs in the society, and many more, which causes illnesses such as fever, cholera, diarrhea, and many more, and also results to deaths of aquatic and marine habitat [5]. Therefore, Nigeria's need to utilize polymeric waste as a wealth-creation solution is fundamental. Discarded plastics containing many hydrocarbons with high calorific value are good sources of such alternate fuels due to their abundant availability and environmental concern for their disposal [7].

Figure 1. Waste high- and low-density polyethylene bags.

1.2. Promising Way of Recycling Waste High- and Low-Density Polyethylene Bags

Nigeria generates millions of tonnes of plastic waste annually, and with the amount set to double by 2034, recycling plastic is vital [8]. There are about 50 different groups of plastics, with hundreds of different varieties. Most types of plastic are recyclable, and because of this, they need to be recycled to reduce the amount of waste sent to landfills and help prevent waste from ending up in the oceans [8].

Wilson [9] identifies the following as some of the benefits of recycling plastic waste materials: Reduces the amount of waste sent to landfills and incinerators, Conserved natural resources such as timber, water, and minerals, Increase economic security, Prevent pollution by reducing the need to collect new raw materials, Saves energy, Protect Ecosystem, wildlife and aquatic animals, Educate people about the importance of protecting the environment, Reduces carbon emission and Create employment opportunity.

Various initiatives have been undertaken to address the issue of polyethylene bags being considered solid waste. Some countries have implemented plastic bag bans or levies to discourage their usage [10]. Furthermore, research and development efforts have focused on finding alternative materials for packaging and promoting recycling programs to reduce the environmental impact of plastic bags [11]. To address this issue, promoting sustainable alternatives to polyethylene bags and implementing effective waste management strategies is crucial. By implementing policies, promoting recycling, and exploring alternative materials, we can mitigate the negative impact of plastic bags on the environment [12]. Conversion of these waste plastics into valuable products is a promising solution since they are energy-rich. It can be achieved by conventional refinery processes such as pyrolysis, gasification, hydrocracking, and catalytic cracking. One of the most promising technologies is the pyrolysis process [13].

2. PYROLYSIS

Pyrolysis is a thermal degradation process involving transforming organic/waste materials into a complex mixture of solid, liquid, and gaseous products in the absence of oxygen. For decades, this process has been used to convert waste materials, such as biomass, plastics, rubber, etc., into valuable products such as biofuels, chemicals, and carbon black [14]. Pyrolysis is a promising technology for waste management and resource recovery due to its potential to reduce waste volume and environmental impact while producing valuable products [14,15].

Pyrolysis of plastics is a process of thermal degradation of waste plastics in the absence of oxygen, which produces valuable products such as pyrolysis oil, gas, and char. The process involves heating waste plastics at high temperatures (typically between 100°C - 500°C) in a pyrolysis reactor, which causes the plastics to break down into smaller molecules and release gas, char, and oil vapors [16,17]. The process is divided into three stages: the initial heating stage, the main pyrolysis stage, and the cooling stage. The reactor's temperature is raised to the desired temperature during the initial heating stage. In the main pyrolysis stage, the waste plastics are heated to the desired temperature, and the pyrolysis reactions occur, producing pyrolysis oil, gas, and char. Finally, the reactor is cooled in the cooling stage, and the products are collected [16, 18]. After upgrading, the pyrolysis oil produced from the process can be used as a fuel in boilers, furnaces, and diesel engines. The gas produced can be used as a fuel for the pyrolysis process, and the char can be used as a solid fuel or an additive in rubber products [18].

The main drawback of pyrolysis oil from waste plastic bags is the oil vapor, which is assumed to be the oil after cooling gives wax; as such, researchers are looking for possible ways to get free oil using a catalyst in the pyrolysis of waste plastics which is Zeolites.

3. ZEOLITES

Zeolites are hydrated aluminosilicates formed by the interlinking of oxygen atoms in tetrahedral alumina ($AlO_4{}^{5-}$) and silica ($SiO_4{}^{4-}$) [19]. The term zeolite was derived from the Greek words "Zeo" and Lithos" [20,21], which means boil and stone, respectively; zeolites have a high ability to absorb water and release it when they get heated [20]. They have an open void with a 3D crystal structure having aluminum, silicon, and oxygen coordination with active metals [21]. The fundamental building blocks of zeolites are terminal oxygen atoms in a tetrahedral structure and center atoms (Al, Si, or O) (Figure 2). By linking between oxygen atoms, they can also generate secondary building blocks that can be formed into rings, prisms, and other sizes (Figure 3). Zeolites are made up of an aluminosilicate framework's basic structure, which consists of four oxygen anions (O^{2-}) surrounding a tetrahedral arrangement of silicon (Si^{4+}) and aluminum (Al^{3+}) ions [21].

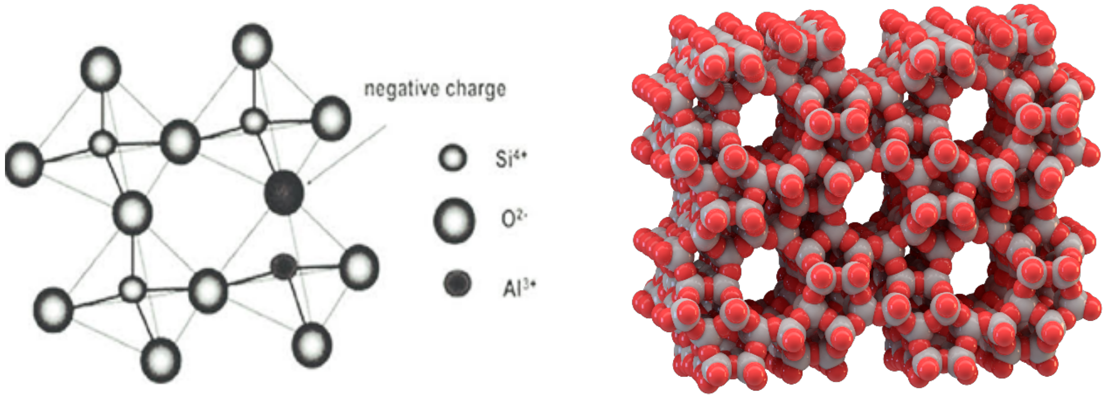


Figure 2. Primary building unit of zeolite; are the ($AlO_4{}^{5-}$) and ($SiO_4{}^{4-}$).

Si-O and Al-O bonds contain oxygen ions connected to two cations shared by two tetrahedron structures [22]. As a result, $SiO_{4/2}$ is tetravalent electroneutral, and $AlO_{4/2}$ is trivalently negatively charged [23]. The negative charge and the pores of zeolites can be occupied by group IA or IIA metal ions and water molecules as it is denoted via the general formula, Mx/n $\{(Al_2O)_x (SiO_2)_y.zH_2O\}$[24,25], where M represents an alkali or alkaline Earth cation, n represents the valence of the cation, z is the number of water molecules per unit cell. X and y are the total numbers of tetrahedral per unit cell.

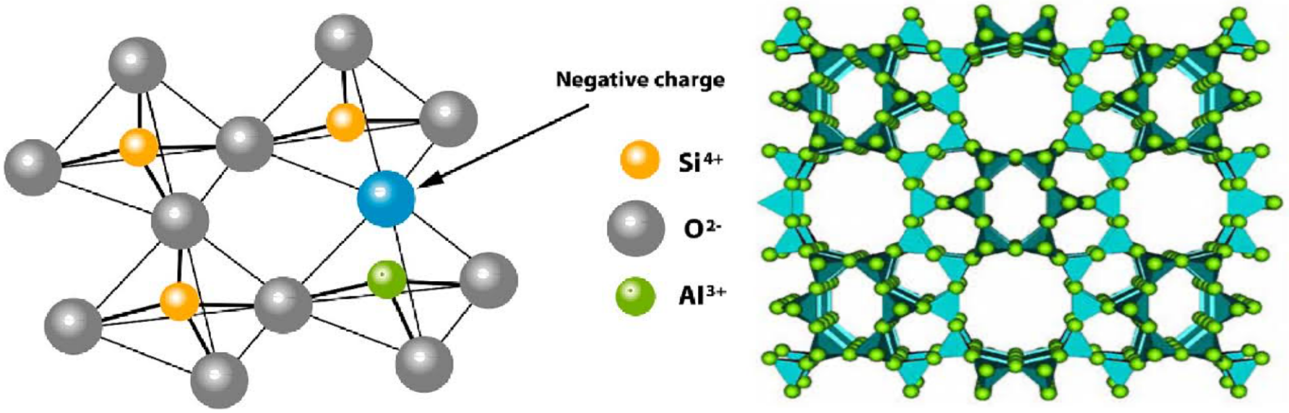


Figure 3. Secondary building unit of zeolite.

3.1. Types of zeolites

Zeolites can be classified into two broad groups: natural and synthetic [25,26]. Most natural zeolites comprise sedimentary and volcanic rocks like mordenite, clinoptilolite, and chabazite [26]. Conversely, heating materials like China clay, feldspar, soda ash, and other materials produce synthetic zeolites [26,27]. Different synthetic zeolites can be made from various materials, including zeolite A, X, Y, and P [28]. Zeolites A, X, and Y comprise cuboctahedral (p-cages) containing tetrahedral SiO_4 and AlO_4 at each framework corner [27,29]. Zeolites X and Y are renowned for having a stiff structure, empty space, and exceptional stability [22]. This class of zeolites is crucial to the manufacturing of gasoline because it catalyzes the cracking of gas oil [30]. The other familiar zeolite is Zeolite A, which is synthesized from sodium aluminosilicate, usually referred to as zeolite NaA or zeolite 4A, represented by the formula $Na_{12} (AlO_2)_{12}(SiO_2)_{12}\cdot 27H_2O$ [27,29]. This synthetic zeolite is used to remediate hard water in detergent manufacturing.

Additionally, it is used to replace sodium tripolyphosphate, a detergent product that is not good for the environment [29]. Also, zeolite 4A has a strong ion exchange capacity and an average particle size range of 4 to 10 µm, which helps avoid dye transfer and graying while washing clothes [30]. Several natural sources, including bauxite, feldspar, coal, fly ash, kaolin, clay, natural oxide, activated carbon, and other silica sources, are used to create zeolites [31]. Zeolites made from natural sources are naturally hydrophilic and have a large specific surface area, high ionic exchange capacity, cheap cost, and highly porous spaces in their structure [26]. In addition, these zeolites are used as the only source of alumina and silica because they are more affordable and plentiful than manufactured zeolites [33,34]. Natural and artificial zeolites are widely used in industrial, agricultural, and biological operations [24,35].

The synthesis, characterization, and surface modification of zeolites and their uses have drawn the interest of several researchers. For instance, Olaremu et al. [19] encapsulated the composition of zeolites using active metals, mainly group alkali and alkali Earth metals, to relieve the Al to Si ratio variation. Wang et al. [24] synthesized Cr-doped TiO_2-supported zeolites to improve their structures, pore size, channels, and absorption ability during photocatalytic activities. Nyankson et al. [25] also reported Zn (II) supported zeolite as the Zn-zeolite framework that generates a secondary pore; the secondary pore results in a larger surface area and can remove dyes, heavy metals, pesticides, and other pollutants from water.

Xiao et al. [36] also reported the solid-state synthesis method in which the initial solid raw material is grounded and mixed without adding solvent [36]. The microwave-assisted method has mild reaction conditions and a high crystallization rate [37]. This method has been developed to promote the nucleation rate of zeolites by increasing the crystallization rate [40]. Omisanya et al. [38] used an adsorbent in a solar refrigerator to create zeolite A using microwave synthesis from Kankara kaolin. Because the continuous-flow synthesis process uses a significant heat transfer coefficient in a tubular reactor, it can complete crystallization in seconds or minutes. [41, 42]. According to Pan et al. [37] research, the zeolite Socony-Socony Mobil-5 (ZSM-5) crystallized from amorphous aluminosilicate gel in less than a minute. The authors confirmed the synthesis method's enormous potential for mass manufacturing of industrial zeolites [43]. The other synthesis method is the solvothermal method, which involves a solvent such as polar solvents and nonpolar solvents [49]. Xiao et al. [37] synthesized pearlite and silica to create faujasite zeolite. To create a synthetic gel, silica and pearlite were combined with a sodium hydroxide solution, and then commercial aluminum hydroxide was dissolved in the sodium hydroxide mixture. After the generated gel was allowed to crystallize for 120 hours at 90 °C, mixed phases of zeolite P, Y, and gmelinite were created [38]. Zeolite was produced by Odebunmi et al. [44] in Erusu Akoko, southwest Nigeria, using kaolin clay. To obtain the necessary silica-alumina ratio, the kaolin clay was transformed into metakaolin at 600 °C and then leached with sulfuric acid [37,44]. Also, an alkaline fusion was carried out to transform the metakaolin into Zeolites Y, X, and P [45]. During the fusion process, sodium hydroxide is added to kaolin, which thermally activates the material to create an active Al and Si species [37, 45]. These species often react to one another before rearranging to create a ring-shaped structure that serves as the foundation for the zeolite framework.

3.2. Application of zeolites

The topic of zeolite products' potential for environmental preservation starts with their industrial manufacture. Since 1954, zeolite manufacturing has attracted industrial interest, and hundreds of thousands of tons of material are produced yearly [46]. The first step in producing a material for environmental protection is the scaling up process because aluminosilicate hydrogels or clay minerals sources that are prevalent in many natural areas and require fewer harmful chemicals as precursors are necessary [47]. Because low temperatures are used, the temperature helps improve energy efficiency. Zeolites also play a significant role in directly developing environmentally friendly industrial processes [46]. Its production is a product protagonist for biomass conversion, fuel cell development, thermal energy storage, carbon dioxide adsorption, wastewater treatment, and the indirect production of fine chemicals and clean technological steps used in industry. It also converts raw materials into over 70,000 everyday products [46].

Zeolite is a catalyst when waste materials are converted into other products. The primary value is energy generation, such as biofuels or compounds from the fine chemistry sector, produced from a renewable source and lowering the amount of waste that builds up in the environment. Zeolites are, therefore, one of the key players in this waste valorization process, speeding up the reactions and encouraging lower manufacturing energy use. For the structure to convert oxygenate chemicals that can produce biofuel additives and their intermediates, zeolites as catalysts must possess two qualities: an acid/base catalyst or a single multifunctional catalyst. The creation of hierarchical zeolites—structures with auxiliary mesoporosity and macroporosity—that improve reaction performance should be emphasized [48]. Since zeolites are utilized to make fuel cells, creating fuel cells—specifically, hydrogen fuel cells—is a contemporary development demonstrating how zeolites can operate in environmentally benign processes. One of the most significant inventions of the modern era is the fuel cell. These devices utilize hydrogen gas molecules to oxidize molecules of oxygen, resulting in the production of water vapor. The high energy generation by weight compared to batteries is the benefit provided. Zeolites have contributed to creating proton exchange membrane fuel cells, which are more energy-efficient than gas and diesel engines and don't produce any hazardous byproducts or pollutants [46-48].

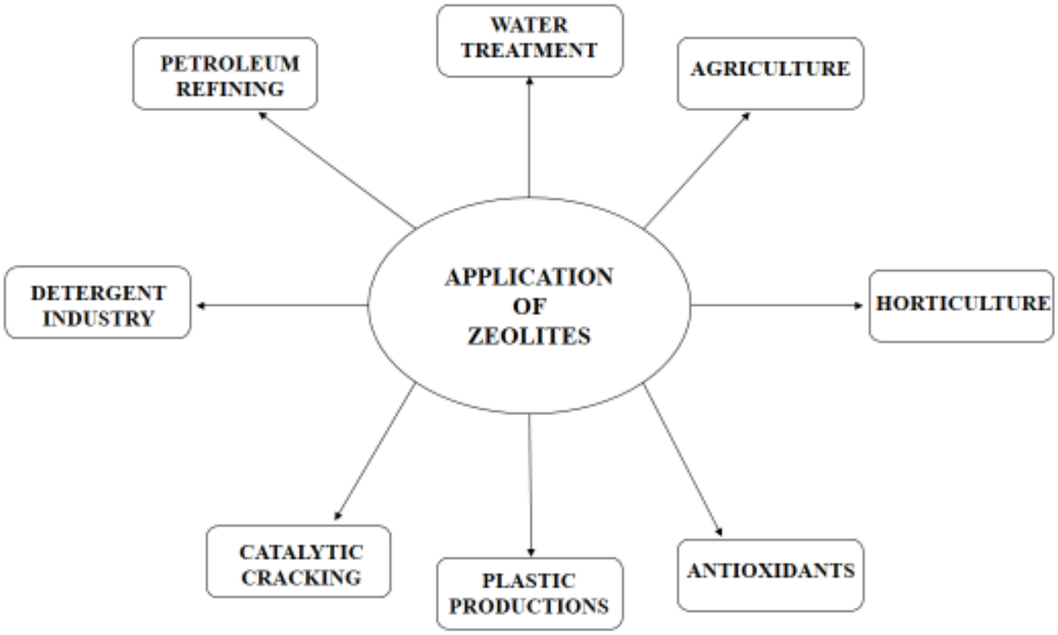


Figure 4. Various application of zeolites.

Due to their inherent characteristics, zeolites are used in a wide range of processes, including membrane separation, coagulation, depolymerization, absorbability, and water purification (Figure 4). These processes are attributed to their porosity and structural variety [30], their homogeneous pore size and shape, the mobility of cations, and the absorbents' and absorbates' hydrophilic and hydrophobic properties [25,49]. Zeolites are still used today to solve a variety of industrial, scientific and environmental issues [50]. This review focuses mainly on the role of zeolites as a catalyst in the pyrolysis of waste high and or density polyethylene bags.

3.3. Catalytic properties of zeolites

The catalytic activities of zeolites result from their active sites (known as Bronsted acid) on the OH bridging framework between silicon and aluminum channel [51,52]. Trivalent elements that replace Si atoms in the zeolite framework provide a negative charge on the lattice that must be counterbalanced by a positively charged counterion [53]. A Bronsted acid site forms when a proton provides the charge balance. The sites, known as bridging hydroxyl sites, are created at every oxygen bridge site close to the Si-O-Al clustering, where protons are the cation that neutralizes the negative charge (Figure 5). The Si-OH-Al sites/ hydroxyl groups are proton donors [54, 55].

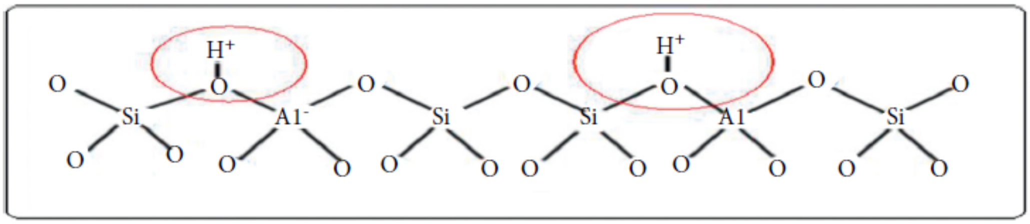


Figure 5. Bronsted acid site in zeolite framework.

In addition, Fattahi [56] reviewed the catalysts' role of zeolites in biodiesel production through transesterification and esterification reactions, as shown in Figure 6.

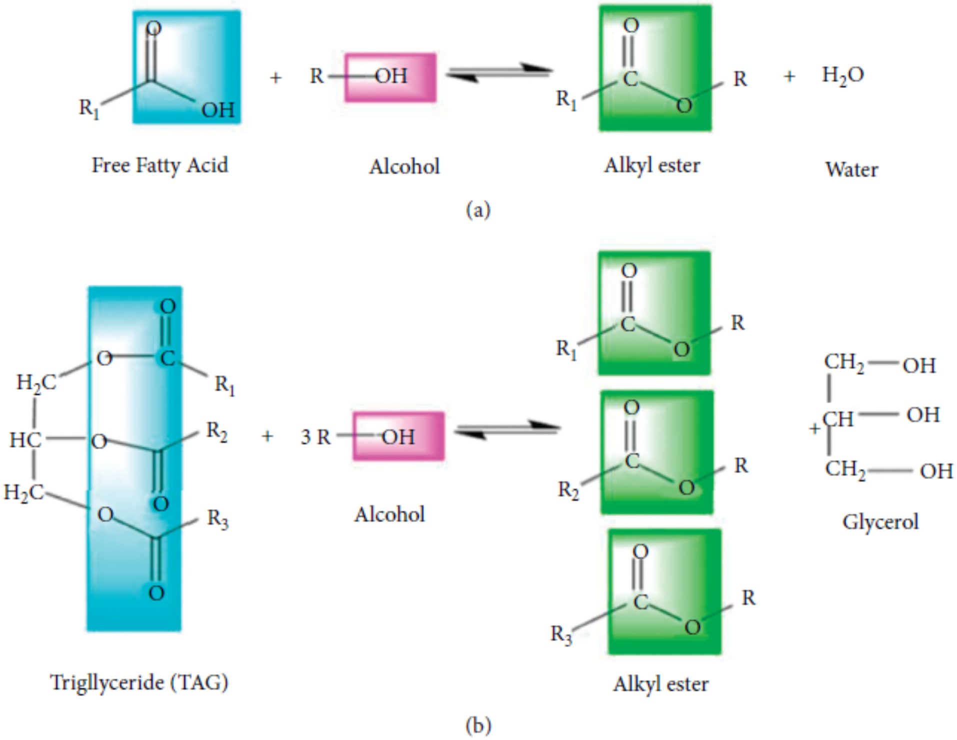


Figure 6. Production of biodiesel (alkyl ester) via (a) esterification and (b) transesterification reaction.

Corma et al. [57] discussed how the reaction conditions- temperature, reactants, pressure, support, metal loading, and particle size- strongly affect the catalyst activity of zeolite as it becomes activated and deactivated during the catalytic process. The atomicity of the metal species may change during reaction conditions and the physicochemical properties of the catalyst, from isolated metal atoms to metal clusters with a few atoms to nanoparticles with tens or hundreds of atoms. The authors concluded that metal atoms may migrate from one porous zeolite site to another across the porous carrier material's channel, pore, or cavity.

In contrast, bimetallic nanoparticles with chemical segregation may be transformed into single-atom alloy nanoparticles under suitable reaction conditions. Encapsulating transition metals and their complexes into zeolites is a promising process that can enhance catalytic activity in different reaction routes. Potential structural transformation of supported single-atom alloy nanoparticles under reaction conditions or change of the atmosphere; segregation may occur with single-atom alloy nanoparticles. To increase catalytic activity and, in particular, catalyst lifespan for possible industrial applications, Pan et al. [58] evaluated the literature on microporous and hierarchical zeolites. To address the mass-transfer problems related to microporous zeolites, Risheng et al. [59] assessed the mesoporous and microporous zeolites in hierarchical zeolites.

4. ZEOLITES AS CATALYST IN PYROLYSIS OF WASTE HIGH- AND LOW-DENSITY POLYETHYLENE BAGS.

A key element in producing wax-free pyrolysis oil is the inclusion of zeolite as a catalyst during the decomposition of used polyethylene bags [38]. Zeolite is well known for its capacity to absorb the wax components, enhancing the pyrolysis oil's quality (figure 7). However, some criteria must be considered to calculate the precise amount of zeolite needed for a given quantity of waste high or low polyethylene bags [38,26]. These comprise the type of zeolite, the exact make-up for the used polyethylene bags, the required level of purity in the pyrolysis oil (figure 8), and the pyrolysis process's operational parameters, such as yield, temperature, and residence time [39].

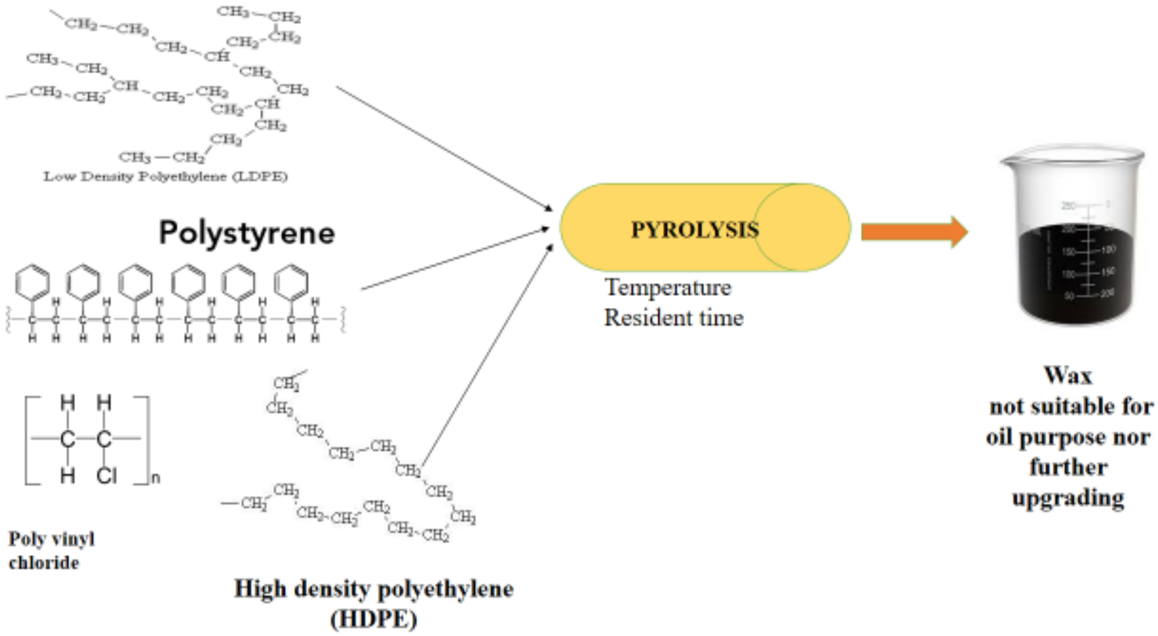


Figure 7. Pyrolysis of Plastic bags.

As zeolite differs from natural or manufactured ones, laboratory testing and optimization should ascertain the optimal amount required. Finding the ideal ratio between zeolite and waste polyethylene should be the goal of several experiments to produce wax-free pyrolysis oil. The zeolite's surface area and pore size should also be considered, as they directly impact its ability to adsorb substances. The required amount will be significantly affected by the type of zeolite selected and its physical and chemical characteristics [32,60].

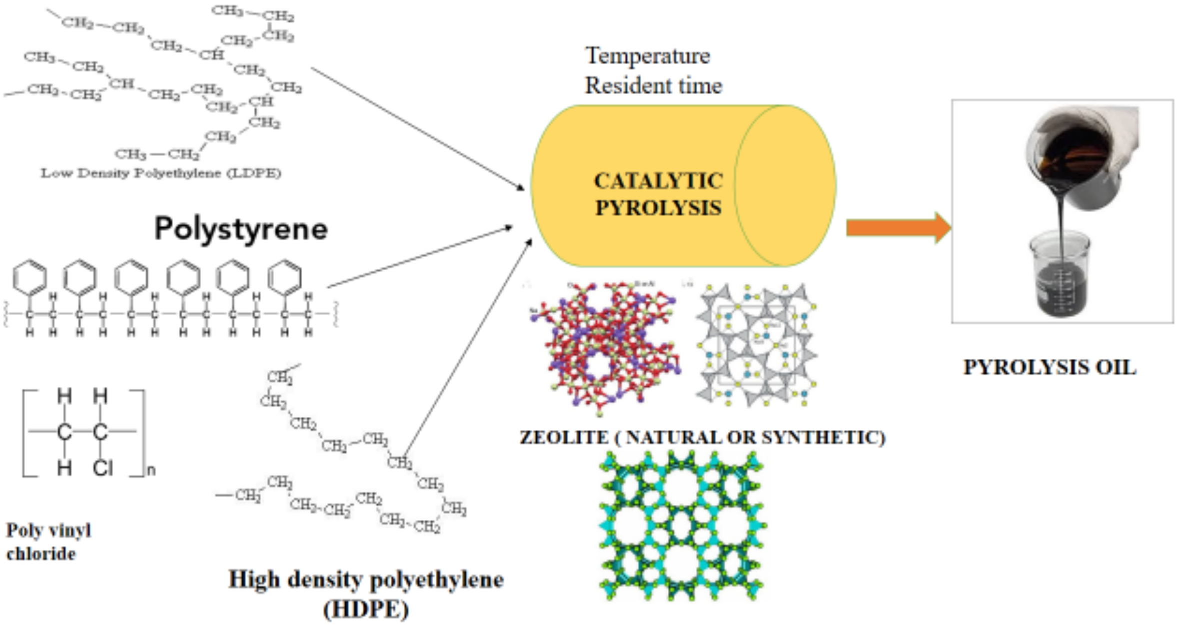


Figure 8. Catalytic pyrolysis of plastic bags.

The amount of zeolite required will also depend on the particular qualities of the waste polyethylene bags, including their molecular weight distribution, contaminant content, and general quality. The final product's intended outcome and the requirements for it to meet must also be taken into account, as this will affect how much zeolite is required [60,61].

5. FUELS AND CHEMICALS FROM CATALYTIC PYROLYSIS OF WASTE HIGH- AND LOW-DENSITY POLYETHYLENE BAGS

Like other pyrolysis processes, oil, char, and gas are the main products at a specific temperature. On the other hand, zinc oxides are used in fluid catalytic cracking (FCC), which is essential for improving pyrolysis fumes. In addition to converting hundreds of compounds in pyrolysis vapors into hydrocarbons, zeolite catalyst forms coke and offers sufficient acidity and shape selectivity [62]. In the past decade, the potential of zeolites in the catalytic pyrolysis of waste high- and low-density polyethylene bags has been broadly investigated. The oil, while collected as vapor, serves as an alternative fuel engine and also gives quite a lot of polycyclic aromatic hydrocarbons (PAHs), such as Naphthalene – NAP, Acenaphthylene – ACY, Acenaphthene – ACE, Fluorene – FLU, Phenanthrene – PHE, Anthracene – ANT, Fluoranthene – FLT, Pyrene – PYR, Benzo[a]anthracene – BAA, Chrysene – CRY, Benzo[b]fluoranthene – BBF, Benzo[k[fluoranthene – BKF, Benzo[a]pyrene – BAP, Dibenzo[a,h]anthracene – DBA, Benzo[g,h, i]perylene – BGP, Indeno[1,2,3-cd]pyrene – IND are all found in the pyrolysis oil depending on the feedstock (type of plastic bags used) due to the catalytic production, the oil is also a potential source of light aromatics such as benzene, toluene and xylene (BTX), in large quantities, which are of valued commodities (figure 9). As reported by Williams and Brindle [63], who used HY and HZSM-5 zeolites in a two-stage pyrolysis process (pyrolysis reactor followed by a catalytic reactor for the gaseous products) and found that generally, increasing the catalyst/feed ratio had a positive effect on BTX yields, with maxima of 5wt% benzene, 24 wt% toluene, 20wt% m- and p-xylenes, and 7wt% o-xylene. The HY zeolite catalyst gave way to higher BTX concentrations than HZSM-5 [64]. Olazar et al. [65] observed the following in aromatic yields: 20.2wt%, without catalyst; 32.5wt%, HZSM-5 zeolite catalyst; and 40.5wt%, HY zeolite catalyst; with BTX maximum yields of 4.15 wt% of benzene, 7.39 wt% of toluene, and 6.59 wt% of xylene using HY zeolite.

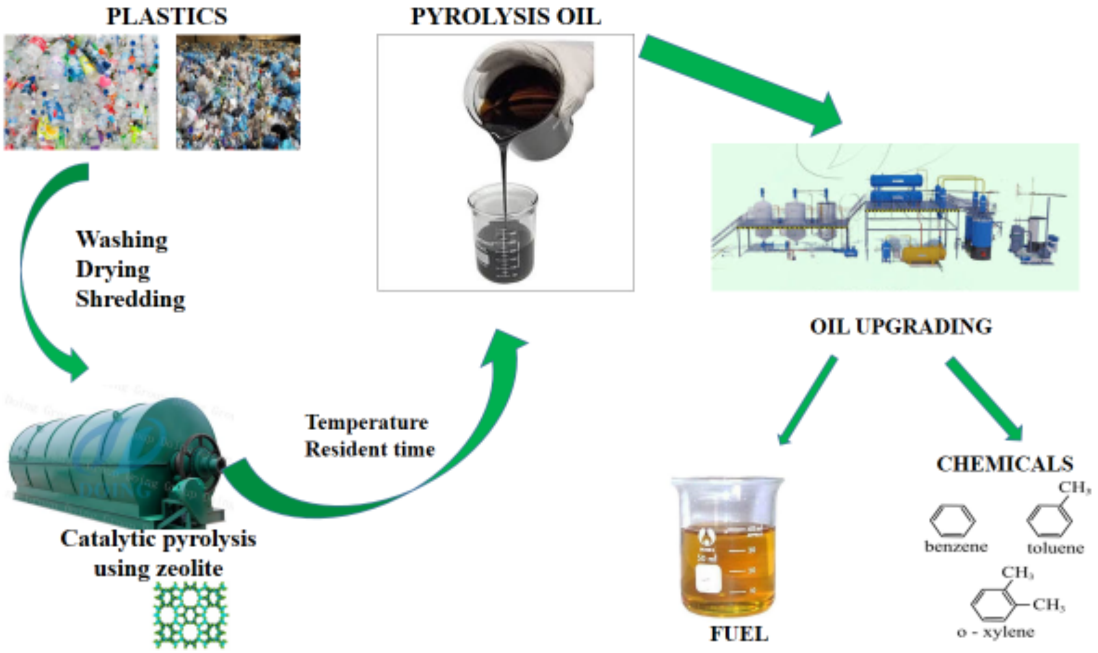


Figure 9. Fuel and chemicals from catalytic pyrolysis of plastics.

Also, as reported by Dai et al. [66], from producing aromatics by zeolite catalysts, light olefins can also be obtained through catalytic pyrolysis using zeolite-based catalysts, these light olefins (ethylene, propylene, and butylene) are mainly origins from petroleum and servers as vital feedstock in the chemical industry can also be obtained. In the catalytic pyrolysis of HDPE with zeolite, it is found that it enhances the liquid yield to 41.39 % and more, which is nearly twice the oil yield compared to ordinary pyrolysis alone as Table 1 shows the comparison of different types of zeolites used in catalytic pyrolysis and the percentage yield obtained. Regarding the oil properties, catalytic-pyrolysis oil shows higher contents of carbon (26% higher), hydrogen (78% higher), and HHV (38% higher) but the absolute absence of oxygen content [62].

TABLE I. Comparison for efficiency catalytic pyrolysis of HDPE bags.

Zeolite name	Yield (wt. %)			Reference
	Oil	Gas	Char	
Zeolite- A	58	41	-	[19]
Zeolite- X	57	42	-	[24]
Zeolite- A	57	40	-	[25]
Zeolite- ZSM + 5	51	48	-	[36]
Zeolite- A	56	43	-	[37]
Zeolite- X	55	42	-	[56]
Zeolite- Y	54	44	-	[58]
Zeolite- HZSM + 5	53	45	-	[59]
Zeolite- X	54	45	-	[63]
Zeolite- HY	56	43	-	[65]

5.1. Production of Benzene, toluene and xylene (BTX) Aromatics

The compounds referred to as BTX are all aromatic and go by three names: "B" for benzene, "T" for toluene, and "X" for xylene. They originate from the thermal cracking of oil and the reforming of naphtha [66]. These aromatics can be obtained using light cycle oil (LCO), an intermediate distillate from the fluid catalytic cracking (FCC) process. Up to 90% of mono-, di-, and trichromatic compounds can be found in LCO. Catalysts playing significant roles in hydrogenation in naphthalene structure and selective cracking of naphthalenic structures—which yields one-ring aromatic hydrocarbons with alkyl chains—achieve the hydrotreating (HDT) and hydrocracking (HCK) processes used in the synthesis of BTX. Another method of producing BTX is the MTA (methanol to aromatics) reaction, which has been made possible primarily by developing methanol generated from biomass, shale gas, and coal via the syngas route [68,69]. BTX synthesis from syngas can reach good selectivity using a dual bed of MnCrOx- ZSM-512-MR zeolites. BTX selectivity is determined by zeolites' architecture and silica alteration of external acid sites. In zeolite topologies like USY, the 12-membered rings facilitate better product production. As a result, syngas have been utilized to provide a catalyst for a one-step synthesis reaction of BTX [70].

Enhancing the production of these compounds requires bifunctional catalysts, preferably with an acidic nature serving as a support and a metal for the hydrogenation and dehydrogenation processes that come after the HDT and HCK reactions before BTX formation [71]. Firm acidity and excessive hydrogenation activity during this process could break molecules, releasing gaseous light hydrocarbons and making them more susceptible to the production of coke [72]. Zeolites play a significant role in this situation as catalytic support primarily due to their robust acidity, excellent thermal and hydrothermal stability, increased resistance to sulfur and nitrogen compounds, decreased propensity to create coke, and tremendous capacity for regeneration [67]. Other characteristics include shape selectivity, allowing the occurrence of specific reactions influenced by the distribution of microporous Brønsted acidity [73]. A catalyst composed of Ni, CoMo, NiMo, and NiSn, when supported over zeolite H-beta, presented good BTX yields that may be improved by adding ZSM-5 zeolite in combination with H-Y. This effect was ascribed to large pores of FAU zeolite, which became an accessible medium for tri-ring aromatic molecules [67].

The intensity of zeolite acidity (Brønsted sites) plays a crucial role in propelling the glycerol conversion process in aromatic compounds. Si/Al ratio also significantly impacts aromatic yield; higher aromatic production is associated with lower Si/Al ratios and higher Al contents. Bentonite is an alternate ingredient that can be added as catalyst support to improve benzene selectivity. One disadvantage of this technique is the creation of coke, which can be eliminated by calcination. The bentonite structure disintegrates during the regeneration phase, lowering the acid strength. Reduced aromatic yield and altered primary processes catalyzed to prevent aromatization are two consequences of a metal altering the zeolitic structure. When using glycerol as a reactant, the temperature significantly impacts the conversion of glycerol to aromatics, and the type of metal used affects the scission of C-O bonds [74].

6. CONCLUSION

The review focused on a two-stage pyrolysis-catalysis process, wherein the type of waste polyethylene bags determines the product yield, composition, and hydrocarbon distribution from the pyrolysis of waste high- and low-density polyethylene. Natural or synthetic zeolites provide clean fuel with a free waxing product that can be upgraded or exposed to additional analysis. Including a catalyst, the oil/wax output dropped to 44–51 wt.%, depending on the HDPE or LDPE and other parameters. On the other hand, the aromatic hydrocarbon content of the pyrolysis-catalysis oils increased dramatically. As a result, the oils' composition changed from being primarily made up of high molecular weight hydrocarbons (C_{16+}) to fuel range hydrocarbons (C_5–C_{15}), including a significant amount of single-ring aromatic hydrocarbons like styrene, toluene, benzene, and ethylbenzene. This approach tackles the pressing problem of disposing of waste HDPE and/or LDPE while demonstrating significant promise for manufacturing chemicals or fuels.

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