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Review Article

Review and Design Overview of Plastic Waste-to-Pyrolysis Oil Conversion with Implications on the Energy Transition

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Plastics are cheap, lightweight, and durable and can be easily molded into many different products, shapes, and sizes, hence their wide applications globally, leading to increased production and use. Plastic consumption and production have been growing since its first production in the 1950s. About 4% of global oil and gas production is being used as feedstock for plastics, and 3–4% is used to provide energy for their manufacture. Plastics have a wide range of applications because they are versatile and relatively cheap. This study presents an in-depth analysis of plastic solid waste (PSW). Plastic wastes can be technically used for oil production because the calorific value of the plastics is quite comparable to that of oil, making this option an attractive alternative. Oil can be produced from plastic wastes via thermal degradation and catalytic degradation, while gasification can be used to produce syngas. Plastic pyrolysis can be used to address the twin problem of plastic waste disposal and depletion of fossil fuel reserves. The demand for plastics has continued to rise since their first production in the 1950s due to their multipurpose, lightness, inexpensiveness, and durable nature. There are four main avenues available for plastic solid waste treatment, namely, reextrusion as a primary treatment, mechanical treatment as secondary measures, chemical treatment as a tertiary measure, and energy recovery as a quaternary measure. The pyrolysis oil has properties that are close to clean fuel and is, therefore, a substitute to fresh fossil fuel for power generation, transport, and other applications. The study showed that plastic wastes pyrolysis offers an alternative avenue for plastic waste disposal and an alternative source of fossil fuel to reduce the total demand of virgin oil. Through plastic pyrolysis, plastic wastes are thermally converted to fuel by degrading long-chain polymers into small complex molecules in the absence of oxygen, making it a technically and economically feasible process for waste plastic recycling. The process is advantageous because presorting is not required, and the plastic waste can be directly fed without pretreatment prior to the process. Products of plastic pyrolysis are pyrolysis oil, a hydrocarbon-rich gas, with a heating value of 25–45 MJ/kg, which makes it ideal for process energy recovery. Hence, the pyrolysis gas can be fed back to the process to extract the energy for the process-heating purpose, which substantially reduces the reliance on external heating sources.

1. Introduction

The world is currently faced with the twin challenge of fossil fuel depletion and strict emission requirements because of global concern over emissions and global warming, leading to the emission targets set at the Paris Agreement [1]. Extraction of oil from waste plastics has attracted the attention of industry and academia as a feasible measure to mitigate the challenge of fossil fuel depletion, clean environment, global warming, and growing demand for fossil fuels [2–4]. The global plastic production has continuously grown despite the fact that recycling rates are comparatively low, with just about 15% of the 400 million tonnes of plastic currently produced annually being recycled. The rate of global plastic production and use has been growing faster than recycling rates over the last 30 years, which implies that more and more plastic wastes are released to the environment. The global production of plastics is forecast to triple by 2050 and is expected to account for a fifth of global oil consumption [5]. Through pyrolysis, a combustible liquid fuel can be produced from waste plastics [6]. These plastic wastes are expected to increase to around 12 billion tonnes by the year 2050 [7]. The industrial-scale production of plastics started in the 1940s and 1950s, with demand and production growing steadily over time. In 2013, about 299 million tonnes of plastics was produced globally [8]. The production increased to more than 322 million tonnes per annum in 2015 [9]. The global production of plastics is currently over 400 million tonnes per annum [10, 11].

The use of plastics generates significant quantities of waste plastics that currently contaminate the waterways and aquifers and limit the landfill areas. Over 14 million tonnes of plastics is annually dumped, and as a result, they cause the death of 1,000,000 species of aquatic life [12]. Common options for plastic waste disposal include feedstock recycling, mechanical recycling, energy recovery, and incineration as municipal solid waste. Incineration of plastics releases noxious odors, harmful gases, dioxins, HBr, polybrominated diphenyl ethers, and other hydrocarbons based on composition [10]. About 15 million tonnes of these plastics reach seas and oceans annually. US emissions from plastic incineration reached 5.9 million tonnes of carbon dioxide in 2015 and will reach about 49 million tonnes by 2030 and 91 million tonnes by 2050. In the past, the United States and other Western countries used to send contaminated waste to China, thus moving responsibility of waste management to China [11]. However, in 2018, China stopped importation of the wastes from Western countries [1].

The global market is dominated by thermoplastic types of polypropylene (PP) at about 21%, low-density polyethylene (LDPE) and linear low-density polyethylene (LLDPE) at about 18%, polyvinyl chloride (PVC) with a market share of 17%, and high-density polyethylene (HDPE) at 15%. Others with high demand are polystyrene (PS) and expandable PS at 8% and polyethylene terephthalate (PET) at 7%, excluding PET fibre and the thermosetting plastic polyurethane. The main challenge with plastic products is that about 40% have a short service life of less than one month [8]. Plastics have a wide range of applications like for making synthetic fibres, foams, adhesives, coatings, and sealants. In Europe, 38% of plastics are used in packaging, 21% are used in building industry, automotive industry uses about 7%, and electrical and electronic applications account for 6%, while other sectors account for 28% of plastic consumption like in medicine and leisure [8, 13].

It has been concluded that waste plastic fuel has similar properties to diesel fuel and can be used instead of diesel [11, 14]. The removal and disposal of huge plastic wastes is a global concern with economic and environmental implications mainly because of population growth, industrialization, and attractive properties of plastic materials [15]. The current rate of economic development and growth will not be sustainable without sustainable and controlled consumption rates of fossil fuel sources of energy [16]. The demand for fossil fuels in power generation, transport, industrial, and domestic applications continues to grow globally while fossil fuel reserves face imminent depletion [17]. The growing population and demand for industrial products and, hence, packing materials have also seen increased use and disposal of plastics as solid wastes [18]. As solid wastes, plastics are undesirable because they are nonbiodegradable [17]. The main advantage of plastics, hence their increasing usage, is that they are cheap, quick to produce, easy to design and fabricate, durable, nonperishable, and recyclable [17, 18]. Synthetic plastic production is about 400 million tonnes, of which about 50% ends up in landfills, while about 15 million tonnes of the plastics ends up in oceans and seas annually [11]. Global plastic production accounts for about 8% of world oil production [19]. Over one trillion plastic bags are produced annually, making them an important end user plastic product globally [20, 21]. Other common forms of plastic wastes include single-use plastics in the form of drink bottles, wet wipes, cotton bud sticks, sanitary items, which are often disposed of via incineration and landfilling [11].

The European strategy recommends a hierarchy of measures in waste prevention and management, beginning with prevention, preparation for reuse, recycling, recovery, and waste disposal [22]. There are four main avenues available for plastic solid waste treatment, namely, reextrusion as a primary treatment, mechanical treatment as secondary measures, chemical treatment as a tertiary measure, and energy recovery as a quaternary measure [23]. Waste recycling is the process of recovering and processing used plastics into useful products. With recycling of plastics, the demand on landfills is reduced, leading to environmental protection, reduced emissions from incineration, and additional socioeconomic benefits [21, 24]. Waste plastics can be processed via catalytic conversion and thermal conversion, which effectively reduce waste pollution, and reduce dependence on fresh or virgin oil for several applications by using pyrolysis oil instead [25]. Waste oil pyrolysis is proving to be one of the energy conversion techniques that yield sustainable energy and a feasible solution to plastic waste disposal for a clean environment [26]. Plastic pyrolysis is a better option to incineration as it allows for energy recovery alongside waste disposal [27, 28].

There is massive growth of plastic production and consumption as a result of urbanization, industrialization, and a cheap supply of plastic materials. Waste plastics have become a nuisance to the land and marine environments, posing significant risks to human and aquatic life [1]. Plastic pollution is a result of limited recycling, yet plastics are generally nonbiodegradable. As an example, out of about 280,000 tonnes of plastics produced in the year 2018, just about 15.3% were recycled, with the rest ending up in landfills, open spaces, and drainages, hence the need for more recycling to reduce plastic waste disposal to the environment [29, 30]. About 50% of plastics produced are disposable and can be dumped, reused, or recycled [31]. The impact of plastics to aquatic life includes the increased presence of microplastics in aquatic ecosystems in the form of spheres, pellets, and fragments. Plastics contain hazardous chemicals like phthalates, polyfluorinated chemicals, and antimitroxide and brominated flame retardants [32]. Brominated flame retardants e.g. PBDEs (polybrominated diphenyl ethers) can cause neurotoxic effects in aquatic microorganisms [25]. Waste Plastics can be used to manufacture oil through the pyrolysis process via a recycling technique which involves degradation of polymeric materials to produce pyrolysis fuel oil that can be used in internal combustion engines and boiler furnaces. However, due to the production of low-yield oil with high acidic content, plastics like polyvinylchloride (PVC) and polyethylene are not ideal for pyrolysis oil production.

The objective of this study is to establish the feasibility of waste plastic pyrolysis to produce fuel from a wide range of plastic materials, e.g., high-density polyethylene (HDPE), polyethylene terephthalate (PET), polystyrene (PS), and polypropylene (PP). Available recyclable wastes are estimated, and a preliminary design specification for a pyrolysis plant is proposed in this research. The study focuses on estimating the plant and process cost as well as final product price development of fuel using the existing pyrolysis technology.

1.1. Problem Definition. New solutions and technologies are needed to address the current challenges facing the plastic industry, i.e., rapid growth in demand and production of plastics and low levels of recycling of used or waste plastics [33–35]. The population growth, economic growth, and global industrialization have led to the generation of huge quantities of wastes, including plastic wastes. Plastic wastes, in particular, plastic bags, bottles, and packaging materials, are visibly littered all over, including in water bodies [36]. Waste combustion generates thousands of pollutants that are harmful to people, especially those living near the incineration facilities. Although landfilling has a lower climate impact compared to incineration, many landfills are full or are getting full. Landfilling also causes soil contamination, water pollution, and may harm to wildlife, flora and fauna[11]. Modern offices, homes, and industries generate huge amounts of plastic wastes that range from packaging materials, electronic parts and equipment, plastic containers, and other forms which are often difficult to isolate and recycle [37]. Plastic wastes are a serious challenge because of the huge quantities being produced and the fact that plastics do not biodegrade for very many years. Plastic products that are heavily produced are the polyolefins, such as polyethylene and polypropylene, which have many applications, like packaging, building, electricity and electronics manufacture, agriculture applications, and health care. The resulting huge wastes are disposed of mainly via land filling [16]. About one-quarter of all plastics produced is made of polypropylene while less than 5% of all plastics are recycled annually. Significant quantities of waste plastics end up in landfills and oceans where they cause pollution and require over 450 years to biodegrade. Conversion of plastics to fuel would create over 39,000 direct jobs, increase the gross domestic product by over $9 billion, and create a cleaner and safer avenue of plastic waste disposal. The quantity and range of plastic products are so huge and continue to grow for various applications. For example, about 1.5 billion tires are manufactured annually around the world. This not only is economically important but also comes with serious challenges of waste disposal and recycling [38]. It costs over $4000 to recycle one tonne of plastic waste, making it attractive to dispose of plastics via burning and landfilling as opposed to recycling which is more expensive [39]. Disposal of plastics via incineration is a major source of emissions globally. In the US alone, incineration of plastic wastes accounted for 59 million tonnes of carbon dioxide in 2015 and will rise to 49 million tonnes by 2030 and 91 million tonnes by 2050 [11]. This makes plastic waste incineration a significant contributor to greenhouse gas emissions [40].

Plastic incineration releases tonnes of pollutants to the surrounding, while landfilling leads to soil and water contamination of the dumpsite and surrounding areas [11]. Land filling is a challenge for many cities like Nairobi in Kenya, where the only dumpsite facility for landfilling located at Dandora is filled and has no space left for more dumping [41].

There are, however, several challenges related to plastic-to-fuel production via pyrolysis which need to be considered. There are some concerns around health risks due to energy recovery from the waste. This is because burning waste plastics emits nitrous oxides, sulphur dioxides, some particulate matter, and other harmful pollutants that are dangerous [1, 30]. However, continuous regulation and pollution control technologies can ensure that emissions are well managed and controlled. Some countries like Sweden which rely so heavily on imported garbage to sustain their industries will be left with a deficit in supplies if wider recycling via the pyrolysis process is adopted. Plastic recycling, like other recycling systems, needs careful planning and adherence to various environmental and industrial regulations and must balance the needs of existing recycling processes [37, 39].

1.2. Rationale of the Study. Plastic waste pollution is a serious problem facing the world today, while at the same time, the production and use of plastics continue to accelerate, yet plastic recycling rates are relatively low, as only close to 15% of the close to 400 million tonnes of plastic are being recycled globally [6]. Plastic production has been growing over the last half century, thus creating a global environmental crisis with most of the over 4.9 billion tonnes of plastics ever produced ending up in landfills [8]. With the looming depletion of fossil fuel sources of energy like gas, diesel, and petrol, it has become increasingly necessary to identify and develop alternative sources of energy to fossil fuels [26]. Plastic recycling offers the lowest environmental impact in terms of Global Warming Potential (GWP) and Total Energy Use (TEU) [42]. Chemical recycling of plastic wastes is simple and cheap and requires little or no sorting where high temperatures are involved [39]. Waste plastic pyrolysis will strongly benefit the fossil fuel industry through improved process sustainability, leading to a cleaner environment and reduced fossil fuel demand via the production of alternative oil. Therefore, research and development in pyrolysis oil production and use is immensely important for a sustainable energy transition involving the controlled consumption of fossil fuels. The various advantages of converting plastic waste into useful fuel coversion includes reduction in carbon emissions by switching from incineration to recycling, recovery of exhaustible or nonrenewable natural resources like resins and rare metals, a lower or reduced carbon footprint of the produced pyrolysis oil compared with the original fossil fuels, development of alternative fuels for transport and other thermal applications, and reduction of landfilling and related pollution [39].

Plastic pyrolysis has created extraordinary attention globally with a number of processing plants currently in operation. A typical example is the recycling plant located at Swindon in the UK operated by Recycling Technologies. The RT7000 plant has the capacity to recycle 7,000 tonnes of plastic wastes, including polystyrene and flexible packaging, to produce 5,250 tonnes of oil for export and local use. The plant employs 130 workers, and the main products are oil, of which 70% is exported for use as sustainable fuel and feedstock for plastic manufacture while the remaining 30% of the products is a wax equivalent product for candle and paint manufacture. Leftover gas and char provide energy for the recycling process. Therefore, production of pyrolysis oil has the potential to displace the use of virgin oil in plastic and lubricant manufacture [5].

Economically, the fuel produced from waste plastics can reduce the import bill and consumption of primary oil, as the oil produced can be used to power transport and for power generation which are the main consumers of fossil fuels. Again economically, these reduces the import bill of non-oil-producing countries, thus saving on foreign reserves, further strengthening local currencies of oil-importing countries leading to a more consumption-sustainable global oil reserve [17].

Plastic pollution is a serious health issue because the various harmful additives used in the manufacture of plastics end up in human and animal body systems. Additives used with health implications are the plasticizers, fire retardants, antioxidants, lubricants, antistatic agents, stabilizers, thermal stabilizers, and pigments. A specific health concern is that these additive substances can mimic, block, and interfere with hormones in the body's endocrine system. As a result, they are classified as endocrine-disrupting chemicals (EDCs) [18]. Other additives are known to be persistent organic pollutants (POPs) [6].

As a result of the failure of conventional approaches to control plastic pollution, globally, a number of authorities have intensified the call for the banning of some categories of plastics from the market. Recycling of plastics is one of the most widely accepted solutions to the growing concern over huge volumes of plastic waste in land and water bodies. Pyrolysis and other thermochemical recycling techniques are, however, associated with challenges associated with need for separation, sorting and cleaning, and high electricity and transport costs, as well as the fear by environmentalists and conservationists that recycling instead of banning will only delay the transition from fossil fuels whose use should be abolished [6, 43, 44].

2. Plastic Production

Plastics are synthetic organic polymers, manufactured from petrochemical materials. The first plastic was invented in the early 1900s, with the type and quantities drastically increasing later for different applications. Plastic management is a serious concern today because increased use of plastics has led to waste disposal challenges as more than 300 tonnes are currently produced per year. In the European Union, about 25% of plastic wastes are recycled as recycling faces challenges like low quality of the recovered and recycled material and products [45]. Between the year 1950 and 2015, some 8300 million tonnes (Mt) of plastics was manufactured globally, of which 6300 million tonnes representing 9% was recycled, 12% was incinerated, and 79% was landfilled [6]. The annual global production of plastics has reached 400 million tonnes in the year 2020 [9, 10]. The production grew by 3.4% between 2014 and 2015. Analysis of annual plastic demand shows a compound annual growth rate (CAGR) of 8.6% between 1950 and 2015 [42, 46].

A significant portion of these plastics ends up in oceans and seas where they disintegrate into microplastics and nanoplastics. These chemical products are consumed by aquatic animals causing a negative impact on zooplankton in terms of population and mortality [6]. Table 1 shows the growth in global plastic production between 1950 and 2020.

From Table 1, it is noted that global plastic production was about 1.5 million tonnes in 1950 and about 400 million tonnes in 2020. This represents a growth of about 266% in global plastic production between the year 1950 and 2020.

3. Plastic Disposal and Recycling

3.1. Plastic Waste Recycling. To attain the best environmental outcome, a hierarchy of measures is proposed in waste prevention and management [41]. The measures are waste prevention, waste reuse, and waste recycling. Plastic waste recycling can be mechanical or feedstock recycling, energy recovery, and final waste disposal. End-of-life treatments for plastic wastes include mechanical recycling, like reprocessing for the production of new products. Plastic recycling transforms the materials to smaller molecules which can be used for the manufacture of new petrochemicals and polymers [42, 47]. Energy recovery techniques include combustion of plastic waste for the production of heat, steam, and electricity. Combustion of plastics is a convenient energy source because of their high energy content. Landfilling is the end-of-life treatments in the hierarchy of plastic waste management [14, 42].

Environmental challenges of plastic wastes can be best addressed through recycling. There are four major types of recycling that can be applied to plastic wastes. These are primary, secondary, tertiary, and quaternary recycling. Through chemical recycling, plastics can be used as feedstock or fuel which reduces the net cost of disposal aside from producing useful energy. Plastics can also be converted into basic petrochemicals which take the form of a hydrocarbon for several process and energy applications [28, 48]. Oil can be processed from waste plastics through thermal degradation, gasification, and catalytic cracking [16]. The main challenge facing plastic recycling is lack of incentives and proper systems for waste collection and separation [14, 49]. Recycling reduces the quantity of waste left available for landfilling and indiscriminate disposal in the environment.

Table 1: Global plastic production between 1950 and 2020 [42, 46].

	Year	Production (million tonnes)
	2020	400
	2015	322
	2014	311
	2013	299
1	2011	280
	2009	250
	2002	200
	1989	100
	1977	50
	1950	1.5

Socially, plastic recycling creates jobs and adds value to the gross domestic product of a country [50].

Many countries globally have made effort to address the challenges of waste plastic besides the ban on production and use of some plastics. Waste plastics are significant, and due to a high and growing demand, the waste menace should be sustainably addressed. In Japan, some 2.75 million tonnes of plastic wastes, mainly PET and PVC, was landfilled or incinerated in 2014 as a result of insufficient recycling options and facilities. The Sapporo Plastic Recycling (SPR) plant was established in the year 2000 for commercial liquefaction in Japan through plastic pyrolysis with a recycling capacity of 50 tonnes/day [51]. Through its cascade facility, the plant mixes plastics from the municipal solid waste stream with waste from other recycling processes in the ratio 40% to 50% of the total feedstock material. Another important innovation from the recycling is that they have learnt to deal with the benzoic acid by converting it to benzene with little or no effect to the fuel potential. Lessons from this plant show that pyrolysis can be done for residues with high PET and PVC content that can be blended with the municipal solid waste plastic stream at up to 40 wt.% with little or no effect to the reactor as well as the product quality [16, 51].

The main products of plastic pyrolysis are light oil, medium oil, heavy oil, and sludge. The common applications of pyrolysis products are solid duel, cogeneration oil, engine fuel, and raw material for further processing to produce plastics and other products.

The six essential steps in waste plastic recycling are as follows:

(i) Plastic waste collection

(ii) Categorization of plastic wastes via sorting

(iii) Cleaning to remove impurities via processes like washing

(iv) Waste shredding and resizing of cleaned plastic waste

(v) Identification and separation of the wastes

(vi) Compounding of plastic wastes [33]

3.2. Types of Recycling

3.2.1. Primary Recycling. Primary recycling is also called mechanical reprocessing, and it involves taking the plastic through the original forming process. The product of primary recycling has the same specification as the original material. The process requires the primary material to be as clean as possible, which makes it relatively expensive and unpopular since a lot of cleaning is required, yet getting clean waste may be a challenge. It is the preferred choice where the waste is easier to sort by resin [16]. The key steps in the primary recycling process are waste separation based on resin and colors, washing or cleaning, and reextrusion into pellets for addition to the original resin [16, 52].

3.2.2. Secondary Recycling. In secondary recycling, the solid plastic waste is mechanically processed into other products. The main benefit of secondary recycling is the conservation of energy needed in the manufacture of plastics to realize some financial advantages [52]. The process can handle contaminated or less separated plastic waste upon cleaning. Secondary recycling uses different products and is not the same as the original production process [16]. Secondary recycling can effectively process unsorted or contaminated waste with less separation, although they should generally be cleaned. The inputs and outputs of secondary recycling range multiple products with outputs being different from the material feedstock. Secondary recycling can be applied for contaminated or less separated waste unlike the primary recycling [30].

3.2.3. Tertiary Recycling/Cracking Process. In the tertiary or cracking recycling process, the plastic waste is broken down at high temperatures in a process broadly referred to as thermal degradation. Thermal degradation can also occur at lower temperatures when suitable catalysts are used in a process referred to as catalytic degradation. The process of tertiary recycling or cracking leads to relative loss in the value of the original plastic material, and the process is more appropriate in cases of high levels of plastic waste contamination. Cracking can be used to recover the monomers of condensation polymers. The processes and mechanisms in tertiary plastic recycling include hydrolysis, methanolysis, or glycolysis [16, 33].

3.2.4. Quaternary Recycling. The quaternary recycling process is preferred for plastic waste with high energy content, hence ideal for incineration. Quaternary recycling involves the recovery of energy, which is the primary objective of the process, and volume reduction. The product of quaternary recycling or incineration usually has significant weight reduction to about 20 wt.% of the original weight and to about 10 vol% of the original plastic waste. The product of quaternary recycling is usually landfilled. The limitations of quaternary recycling are the generation of solid waste and air pollution from plastic combustion [16, 33].

4. Methods of Plastic-to-Oil Conversion

There is growing importance of plastic-to-fuel conversion due to increasing awareness and evidence of environmental degradation caused by plastic wastes, especially the single-use plastics amidst people's limited recycling habits [53]. It is estimated that less than 5% of manufactured plastics are recycled, yet production is projected to increase 3.8% annually until the year 2030, with about 6.3 billion tonnes having been produced since plastic production started over 60 years ago. A significant fraction of these plastics ends up in seas and oceans, causing disruption of the marine environment. It is estimated that these plastics can take a minimum of 450 years to biodegrade. Economically, it is estimated that plastic-to-fuel investment will create about 39,000 jobs and about $9bn in economic output [53]. Plastics can be converted to fuel in the form of hydrogen, crude oil, diesel, and sulphur.

4.1. Plastic to Hydrogen Fuel. Hydrogen is normally produced commercially via catalytic steam reforming of natural gas, naphtha, and hydrocarbons. There is growing interest in alternative feedstock for hydrogen production mainly because of concerns over the security of supply and price instability. Hydrogen can be produced from plastics, especially the polyolefins [54]. As a major development in the waste plastic to fuel, researchers from Swansea University were able to convert plastic waste into hydrogen fuel via addition of a light-absorbing photocatalyst to the plastic material for the absorption of sunlight that then transforms it to chemical energy in the process of "photoreforming." In this process, the plastic and catalyst mixture is put into an alkaline solution and exposed to sunlight, which leads to a chemical breakdown and production of hydrogen gas [53]. At Oxford's Department of Chemistry, particles of mechanically pulverised plastic were mixed with a microwave-susceptor catalyst of iron oxide and aluminium oxide and subjected to microwave treatment that produced a large volume of hydrogen while a carbonaceous residue material that formed was mainly of carbon nanotubes. This proved that 97% of hydrogen in plastic can be recovered in a short time period directly with no carbon dioxide emission [7].

In the study by [55], hydrogen gas was produced from polyethylene waste via a two-stage pyrolysis–low-temperature plasma catalytic steam-reforming process carried out at about 250°C. This produced pyrolysis gas that was catalytically steam-reformed in the presence of low-temperature nonthermal plasma in the form of a dielectric barrier discharge to produce hydrogen gas. The hydrogen yield was increased in the absence of a catalyst by increasing the plasma power. Various catalysts that can be used in hydrogen production include Ni/Al_2O_3, Fe/Al_2O_3, Co/Al_2O_3, and Cu/Al_2O_3. Tests showed that the Ni/Al_2O_3 catalyst resulted in the highest yield of hydrogen at 1.5 mmol/g of plastic used. Investigation on the impact of steam addition to the plasma catalytic process at different steam weight hourly space velocities (WHSVs) with Ni/Al_2O_3 as the catalyst showed that steam promotes catalytic steam-reforming reactions leading to more hydrogen production. The highest yield realized was 4.56 mmol/gram of plastic at a WHSV of $4\,g\,h^{-1}\,g^{-1}$ catalyst [55]. Therefore, plastic-to-hydrogen fuel conversion is a feasible process and, hence, a promising plastic-to-green-energy pathway.

4.2. Plastic to Diesel. In this conversion, plastics are broken down with heat and/or reactive, toxic chemicals, which results into the breaking of the plastic material bonds. This process can produce a liquid fuel that can be used to run engines for transport and industrial applications. The catalysts selected have to be compatible with various types of polyolefin additives so that plastic wastes can be processed without pretreatment, making it easier and cheaper [39].

4.3. Plastic to Crude Oil. Plastics have successfully ben converted to crude oil via pyrolysis of high-density polyethylene bags. The plastic crude oil produced can be refined via fractional distillation to produce gasoline and two different types of diesel [39]. By adding antioxidants, the oil product made is superior to conventional diesel fuels in terms of parameters like lubricity and derived cetane number, which is a measure of combustion quality of a diesel fuel [53].

4.4. Plastic to Sulphur. Waste plastics can be converted to sulphur fuel by using the discarded material as feedstock [39]. This technique is, however, still under research and development with the main concern being the application of sulphur as a fuel when the main environmental concern is to limit sulphur dioxide emissions [1].

5. Plastic Pyrolysis

One of the feasible processes in converting plastic waste into fuel is through pyrolysis. Pyrolysis is a complex series of reactions that are both chemical and thermal that depolymerize an organic material in the absence of oxygen [56]. The process requires the heating of plastics to a high temperature, and then, the volatile material is distilled or separated for reuse as an energy material [39]. In waste plastic pyrolysis, the plastic waste material is subjected to high temperatures in the absence of oxygen and the presence of a catalyst to help in the gentle cracking of long chains. The gases produced are condensed in the condenser to yield low sulphur content-distilled waste plastic oil [17, 18]. The use of catalysts prevents the formation of dioxins and furans (benzene ring) during the process [17]. Thermal degradation of plastics decomposes plastics' three main fractions, namely, gas, crude oil, and solid residue. The crude oil consists of the higher boiling point hydrocarbons from the noncatalytic pyrolysis process. Efficient production of gasoline and diesel from plastic wastes requires optimization of parameters like catalysts used, pyrolysis temperature, and plastic-to-catalyst ratios. The quality of crude oil can be improved by copyrolysis of plastics with coal or shale oil which reduces the viscosity of the crude oil produced [25]. Processes used in the conversion of plastics to fuels include gasification, pyrolysis, plasma process and incineration. In pyrolysis, plastic wastes are converted into solid, liquid, or gaseous fuels via the thermal degradation of long-chain polymers into shorter and simple molecules in the absence of oxygen. The main products of pyrolysis are combustible gas with high calorific value, combustible oils, and carbonized char [20].

Pyrolysis refers to the process of converting plastics into solid, liquid, or gaseous fuels through thermal degradation of long-chain polymers into less complex molecules in the absence of oxygen. The products of pyrolysis include high calorific gas, high quality oils, and carbonized char. Pyrolysis can produce as high as 80 wt.% at moderate conditions and requires temperatures of 300–900°C [57, 58]. The main processes are slow, fast, flash, and catalytic plastic pyrolysis [14, 59]. The various types of pyrolysis are conventional pyrolysis (slow pyrolysis), which proceeds under a low heating rate with solid, liquid, and gaseous products in significant portions. It is an ancient process used mainly for charcoal production [14, 59]. Vapors can be continuously removed as they are formed. Fast pyrolysis, which is associated with tar, can proceed at lower temperature (850–1250 K) or at high temperatures with a gas (1050–1300 K). Others are thermal pyrolysis and catalytic pyrolysis [20, 60]. Fast or flash pyrolysis is the most preferred technology, and it takes place at high temperatures and short residence time. Fast pyrolysis is also called thermolysis and involves rapid heating of a carbonaceous material to high temperatures in the absence of oxygen.

Pyrolysis technology has been improved over the years to produce valuable liquid oils via valorization of organic materials. The process still faces challenges that arise from the use of the different feedstock types. Critical to the success of pyrolysis is the design of new reactor types to optimize product yields while, at the same time, minimizing energy consumption and process costs. Pyrolysis is a mature technology with a number of commercial plants in operation for biomass and plastic feedstock. Pyrolysis can be effectively used to treat various plastic wastes ranging from packaging waste to more complex plastic materials like rubber and WEEE (waste electrical and electronic equipment), ELV (end-of-life vehicle), and hospital waste that are often contaminated with toxic and hazardous substances. Products of plastic pyrolysis are pyrolysis oil, a hydrocarbon-rich gas, with a heating value of 25–45 MJ/kg that makes it ideal for process energy recovery and char. Hence, the pyrolysis gas can be fed back to the process to extract the energy for the process-heating purpose that substantially reduces the reliance on external heating sources [33]. Figure 1 below demonstrates a pyrolysis process with inputs and product outputs.

Figure 1 above shows the main elements of the plastic pyrolysis process, namely, the feed preparation chamber, reactor, char collector, fuel storage tank, and cyclone.

The waste plastics are mixed and heated in the absence of oxygen in a process called cracking, which leads to production of a gas. The gas or vapor is distilled into products ranging from heavy wax and oils to light oils and gas. Most of these products have a potential to provide new building blocks for new polymers or can instead be used as fuel [5]. Figure 2 demonstrates the plastic pyrolysis process.

From Figure 2, it is noted that the main elements of a plastic pyrolysis process plant are the reactor, condenser, fractionating tower, and condenser.

A pyrolysis plant can recycle even the hard-to-recycle plastics like polystyrene and flexible packaging into 75% liquid oil, which can be used as sustainable fuel and plastic manufacture feedstock. The remaining 25% can be used as a wax equivalent for the manufacture of candles and paint, while the produced gas and char can be used as energy sources for the plant [5]. The most common technology used in plastic waste disposal is the thermal treatment that generates heat for either process-heating applications or steam generation and power production [22]. The process starts by feeding a cylindrical chamber where heating is done. In thermal pyrolysis, plastics are heated in inert conditions to decompose organic parts into liquid and gaseous fuels. However, thermal pyrolysis results in lower-quality fuels due to high temperatures as the products have a lower molecular weight [62].The generated pyrolytic gases are condensed in a condenser system, to produce a hydrocarbon distillate. The distillate is comprised of straight- and branched-chain aliphatic, cyclic aliphatic, and aromatic hydrocarbons. These products are separated by means of fractional distillation to produce liquid fuel products. Plastic pyrolysis takes place at 300°C–9000°C. The plastic is first evenly heated to a narrow temperature range without excessive temperature variations, followed by purging oxygen from the plastic pyrolysis chamber. The third step involves managing the carbonaceous char byproduct before it acts as a thermal insulator and lowers the heat transfer to the plastic. The final stage involves condensation and fractionation vapors to produce a distillate of good quality and consistency [16].

The pyrolysis process can occur under varying operating conditions, which can be used as the basis of classification [59]. They can be distinguished on the basis of the residence time requirement for the pyrolyzed material in the reactor, feedstock particle size, pyrolysis process temperature, and process heat rate among others. Four mechanisms are involved in the thermal degradation of plastics. These mechanisms are the end-chain scission or unzipping mechanism, random-chain scission/fragmentation mechanism, chain stripping/elimination of side-chain mechanism, and cross-linking mechanism. The mode of decomposition is a function of the type of polymer, i.e., the molecular structure; for example, cross-linking is common in thermosetting plastics when heated to a high temperature that causes two adjacent "stripped" polymer chains to form a bond resulting in a chain network like in char formation [1, 16].

5.1. Catalytic Pyrolysis. In catalytic pyrolysis, a suitable catalyst is used to facilitate the cracking reaction by lowering the reaction temperature and process time [1]. Catalytic pyrolysis is cheaper and, hence, economically attractive [63]. The optimization strategy in catalytic pyrolysis is to minimize the use of the catalyst through reuse and the use of low quantities of catalysts. The benefits of catalytic pyrolysis include cost-effectiveness, less pollution from plastic wastes, and less solid residues [1].

The process of catalytic-cracking pyrolysis involves heating the plastic material in an inert environment in the presence of catalysts. The temperature range for catalytic cracking is between 350°C and 550°C. This process can be applied for the recycling of either pure or mixed plastics. It

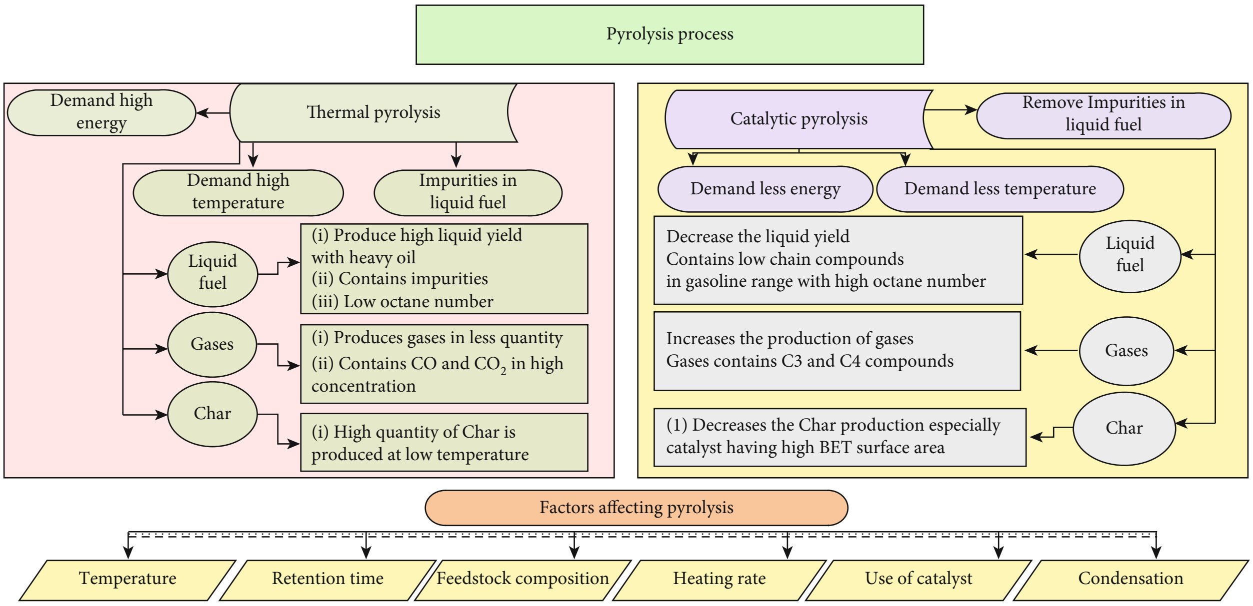

Figure 1: Industrial waste plastic-to-oil pyrolysis plant [2, 61].

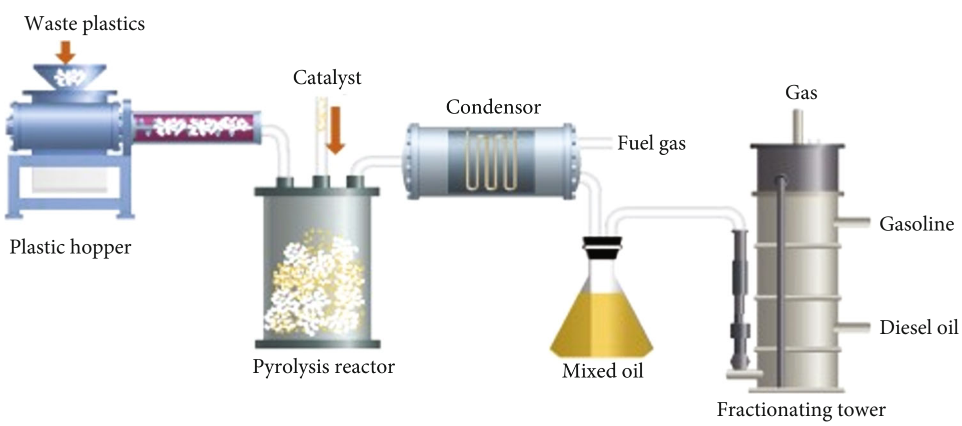

Figure 2: Plastic pyrolysis process description [5].

yields higher quality fuel oils as compared to thermal pyrolysis. The catalyst promotes decomposition reactions at low temperatures with low energy consumption, reduced costs, faster cracking reactions, increased process selectivity, and increased yield of products with high added value [21]. In this process, a cracking vessel is used for the storage of the melted waste plastic in which the primary heating component for heating the waste plastic is done from a surface at the base of the cracking vessel with a second-level heating being done at the upper surface of the cracking vessel. A cooling vessel is used for cooling the cracked gas vaporized in the cracking vessel, which results in a cracked oil byproduct [37].

5.1.1. Mechanism of Catalytic Degradation

(1) Depropagation. This is achieved via the reduction in the molecular weight of the main polymer chains through successive attacks by acidic sites or carbonium ions and chain cleavage, yielding approximately C_{30}–C_{80}. Further, cleavage of the oligomer fraction, like through direct β-emission of end-chain carbonium ions, produces a gas and a liquid fraction (approximately C_{10}–C_{25}).

(2) Isomerization. In the isomerization mechanism, the carbonium ion intermediates are rearranged via hydrogen- or carbon-atom shifts, which then leads to a double-bond isomerization of an olefin. Some other isomerization reactions include the methyl-group shift and isomerization of saturated hydrocarbons.

(3) Aromatization. The intermediates of the carbonium ion can undergo cyclization reactions, for hydride ion abstraction may first take place on an olefin at a position removing several carbons from the double bond that results in the formation of an olefinic carbonium ion. Then, the carbonium ion may undergo an intramolecular attack on the double bond.

5.1.2. Process/Steps. The steps involved in catalytic cracking are initiation, propagation, and termination.

(1) Initiation. This stage involves random breakage of the C–C bond on the main chain, which occurs upon heating to produce hydrocarbon radicals.

(2) Propagation. In the propagation stage, the hydrocarbon radical is decomposed into lower hydrocarbons such as propylene, followed by β-scission and abstraction of H-radicals from the other hydrocarbons resulting in a new hydrocarbon radical.

(3) Termination. This stage involves the disproportionation or recombination of two radicals: this involves the catalytic degradation with iron-activated charcoal in the presence of hydrogen. The hydrogenation olefin, i.e., hydrocarbon ion and the abstraction of the H-radical in the HC (hydrocarbon) or HC radical, would produce a radically improved or enhanced degradation rate. For reactions that occur below 400°C as well as fast reactions taking less than 1 hr, the existence of hydrocarbon radicals in the reactor is high, which readily causes recombination of these radicals as they do not move fast. As for iron- (Fe-) activated carbon in the presence of hydrogen, the radicals are hydrogenated, which suppresses recombination. Therefore, the decomposition of the solid products is promoted. The same applies for the low polymers whose molecular diameter is larger than the catalysts' pore size [16, 64].

5.2. Characteristics and Application of Pyrolysis Oil. Pyrolysis oil has similar characteristics with light fuel or gas oil and has proven to be a good furnace and engine oil but requires property modifications [38]. Modification can be achieved by the use of alcohols to modify corrosiveness, acidity, ignition temperature, calorific value, and volatility, as well as energy density. Blending with alcohols also reduces the negative environmental impact caused by pyrolysis oils. For use as an engine fuel, blending with up to 20% alcohol can be done with no engine modifications. The higher latent heat of vaporization of methanol and ethanol compared to diesel initiates a longer ignition delay period of combustion with pyrolysis oil.

Pyrolysis oil from tires and plastics has been tested and proven to be a feasible diesel engine fuel and has comparable properties to conventional diesel oil. The oil is a complex mixture of C_5–C_{20} organic compounds. However, oil from tire pyrolysis contains a higher proportion of aromatics and a sulphur content as high as 1.4%. Unsorted plastics may also lead to higher chlorine content. There is, however, need for more research on the costs of substituting fossil fuel with pyrolysis oil [56].

Oil from plastic wastes has a higher sulphur content compared to the conventional fuel, making it unattractive as an automobile fuel, and increases sulphur dioxide emissions that are a major contributor to acid rain. In a study on oil from the pyrolysis of high-density polyethylene, the waste plastic pyrolysis oil (WPPO) was found to have a sulphur content of 0.246%, which is significantly higher than that of conventional gasoline, kerosene, and commercial grade diesel. The conventional diesel has about 0.15% sulphur, while gasoline contains about 0.014% sulphur making them claener than the waste plastic pyrolysis oil (WPPO) [6]. Figure 3 below shows the sulphur content of waste plastic pyrolysis oil (WPPO), heavy fuel oil, furnace oil, diesel, kerosene, light fuel oil, and gasoline.

From Figure 3, it is noted that the pyrolysis oil of waste plastic has a higher sulphur content compared with conventional diesel, kerosene, light fuel oil, and gasoline. However, its sulphur content is lower compared to that of heavy fuel oil and furnace oil which are widely used for power generation and industrial heat generation, which makes waste pyrolysis oil a cleaner substitute for heavy fuel oil (HFO) and furnace oil.

The flash point for pyrolysis oil from plastic waste is <40 degrees Celsius, but the exact value varies based on the type of plastic used as feedstock, for example, a single feed plastic like polyethylene yields oils with flash point as low as 10 degrees compared to the flash point of conventional diesel being about 50 degrees. The low flash point is an indication of high volatility which is a safety concern in transportation [6].

The oil from tire pyrolysis yields a better engine performance while the heating value of the plastic pyrolysis oil is higher than that of the tire pyrolysis oil. Economically, the pyrolysis oil can replace the conventional diesel oil in terms of engine performance and energy output as long as the price of the pyrolysis oil is less than 85% of the price of conventional diesel [56, 65]. According to [5], crude oil prices above \$65 per barrel are necessary to justify commercial investment in waste plastic to fuel without a premium, but with a green premium, recycling waste plastic to fuel is still viable at prices below \$65 per barrel. A diesel engine was noted to give better performance when using fuel containig pyrolysis oil of up to 30%, and it may perform well with a maximum of up to 50% of the waste plastic oil blended into conventional diesel fuel. In another study by [16, 66], it was observed that an engine has a stable performance with the brake thermal efficiency being comparable to that of conventional diesel, and the value of the brake thermal efficiency is higher with the pyrolysis oil by up to about 80% of the engine load. However, the engine emissions were notably higher with pyrolysis oil compared to conventional diesel [56]. In a study on a petrol engine fueled by waste pyrolysis oil, the engine had a higher brake thermal efficiency of up to 50% of the petrol engine rated load. The higher calorific value and more oxygen content of the waste pyrolysis oil leads to higher heat release rates [17, 67, 68]. In another study by [17, 69], it was observed that the high viscosity with blends is the reason for poor atomization, which leads to a longer ignition delay and a longer combustion duration compared to conventional diesel when tested at full load. In other studies, by [17, 70–72], it was noted that the use of the waste plastic pyrolysis oil increases the ignition delay by about 2.50 CA. The study also noted an increase in emissions with NOx increasing by 25%, CO increasing by 5%, and unburned hydrocarbon increasing by about 15%, and smoke, although smoke was reduced by 40% to 50%. In yet

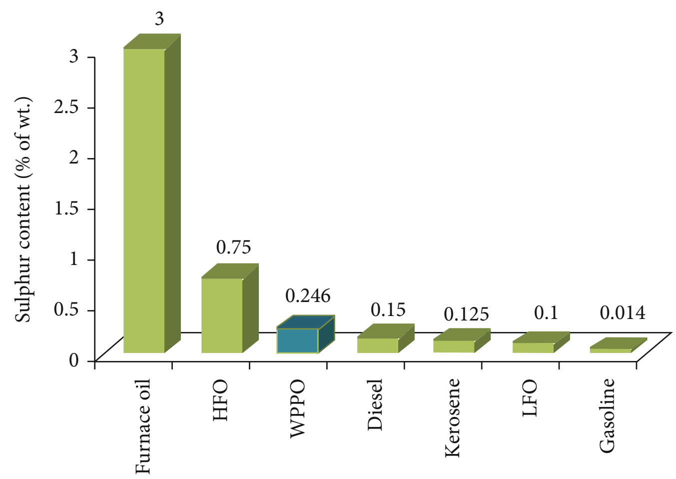

Figure 3: Sulphur content for various oils [6].

another study by [73], the waste plastic pyrolysis oil yielded a brake thermal efficiency (BTE) of 27.75% compared to 28% for diesel, brake-specific fuel consumption (BSFC) of 0.292 kg/kWh compared with 0.276 kg/kWh for diesel, unburned hydrocarbon emission (uHC) of 91 ppm compared with 57 ppm for diesel, and NO_x emission of 904 ppm compared with 855 ppm for conventional diesel.

An important parameter in the combustion performance is the injection timing for all compression ignition engines. In the study by [6], the injection timing varied for an engine. The study showed that by changing the injection timing from 230 bTDC (before top dead center) to 140 bTDC (before top dead center), the emissions for NO_x, CO, and unburnt CO were reduced. In the study by [74], it was experimentally established that the brake thermal efficiency of blends is lower than that of conventional diesel, but at 25% blending, there was a similar performance between the blend and pure diesel as a fuel for the engine [67]. Therefore, the plastic pyrolysis oil could improve the engine performance through modification like injection timing. Economically, the pyrolysis oil can replace diesel in terms of the engine performance and energy output on the condition that the cost or price at the point of usage is not more than 85% of conventional diesel oil [75] if crude oil prices are more than US$65 per barrel [5].

5.3. Oil Yield of Different Plastics. There are three major products of pyrolysis of plastic waste, namely, liquid oil, gas, and solid residue or char. Liquid oil results from condensation of vapors released from the reactor, whereas gas is obtained from the noncondensable vapors and solid residue remains in the reactor [58, 76, 77]. In studies by [78–80], the liquid oil, gas, and solid residue were analyzed for their composition, yield percentages, and potential applications. Liquid oil is the dominant of the products, followed by gas and finally the solid residue. However, the process conditions, such as temperature, use of catalysts, feedstock type, and retention time, could be altered to favor production of either liquid or gas. Additionally, Reference [79] showed that calorific values for the liquid oil produced from the pyrolysis of HDPE, PP, and LDPE plastic wastes were close to those of commercial diesel and gasoline. For PS, PVC, and PET, low calorific values were attributed to an aromatic ring within the PS chemical structure, chlorine in PVC, and benzoic acid in PET. The kinematic viscosity, density, and flash point of the pyrolysis oil showed values near those of commercial diesel and gasoline [58]. According to [78], pyrolysis oil can be used as a good transport fuel when blended with diesel in ratios of 10%, 20%, 30%, and 40% that produced various engine performance characteristics. Table 2 compares liquid oil properties with those of commercial grade diesel and gasoline.

From Table 2 above, it is noted that different plastics produce different outputs in terms of composition of the main products, i.e., oil, gas, and char. In terms of calorific value, polystyrene (P) produces oil with the same calorific value as conventional diesel, but it has a significantly lower flash point; hence, it is more flammable and more viscous and has a higher density than diesel. Oil from PVC has the lowest calorific value. The pyrolysis oil is more viscous and has a lower flash point than conventional diesel. Compared to petrol, the pyrolysis oil has a higher density, but its flash point may be less or higher than the pyrolysis oil depending on the oil source or plastic used [30].

The quality of the pyrolysis oil is a function of both the type of plastic and the process used. Table 3 below is a summary of the process, type of plastic, and product quality realized.

Table 3 above shows the various plastics, oil yield potential, and optimum conditions for pyrolysis and solid waste generation. The pyrolysis temperature used is between 350 and 740°C. The highest oil yield is 97% of the oil yield from polystyrene processed in a batch reactor at 425°C.

Fuel can be produced from plastics through gasification, thermal pyrolysis, and catalytic pyrolysis. Catalytic pyrolysis of homogenous waste plastics generates better oil in terms of both quantity and quality. The main product of gasification is syngas at a higher temperature than those realized in the pyrolysis process. Syngas can be used as a feedstock for the Fischer-Tropsch (FT) process for the production of diesel

Table 2: Physical properties of pyrolysis oil from different plastic wastes [81].

Property	PET	HDPE	PVC	LDPE	PP	PS	Gasoline	Diesel
Calorific value (MJ/kg)	28.2	40.5	21.1	39.5	40.8	43.0	42.5	43.0
Density (g/cm^3 @ 15°C)	0.9	0.89	0.84	0.78	0.86	0.85	0.78	0.807
Viscosity (mm^2/s)	—	5.08	6.36	5.56	4.09	1.4	1.17	1.9–4.1
Flash point (°C)	—	48	40	41	30	26.1	42	52

Table 3: Summary of plastic pyrolysis studies [46].

Plastic type	Reactor	Process parameters				Yield			
		Temp. (°C)	Pressure	Heat. rate (°C/min)	Time (min)	Oil	Gas	Solid	Others
PET	Fixed bed	500	—	10	—	23.1	76.9	0	
PET	—	500	1 atm	6	—	38.9	52.1	8.98	
HDPE	Horizontal bed	350	—	20	30	80.9	17.2	1.88	
HDPE	Semibatch	400	1 atm	7	—	82	16	2	Stirring rate 200 rpm, FCC catalyst, 10 wt.%
HDPE	Batch	450	—	—	60	74.5	5.8	19.7	
HDPE	Semibatch	450	1 atm	25	—	91.2	4.1	4.7	Stirring rate 50 rpm, FCC catalyst 20 wt.%, silica-alumina catalyst
HDPE	Fluidized bed	500	—	—	60	85	10	5	
HDPE	Batch	550	—	5	—	84.7	16.3	0	
HDPE	Fluidized bed	650	—	—	20-25	68.5	31.5	0	
PVC	Fixed bed	500	—	10	—	12.3	87.7	0	
PVC	Vacuum batch	520	2 kPa	10	—	12.79	0.34	28.13	HCL, 58.2 wt.%
LDPE	Pressurized batch	425	0.8-4.3 MPa	10	60	89.5	10	0.5	
LDPE	Batch	430	—	3	—	75.6	82	75	Wax =8.7 wt.%
LDPE	—	500	1 atm	6	—	80.4	19.43	0.16	
LDPE	Fixed bed	500	—	10	20	95	5	0	
LDPE	Batch	550	—	15	—	93.1	14.6	0	
LDPE	Fluidized bed	600	1 atm	—	—	51.0	24.2	0	Wax =24.8 wt.%
PP	Horizontal steel	300	—	20	30	69.82	28.84	1.34	
PP	Batch	380	1 atm	3	—	80.1	6.6	1.33	
PP	Semibatch	400	1 atm	7	—	85	13	2	Stirring rate 200 rpm, used FCC catalyst 10 wt.%
PP	Semibatch	450	1 atm	25	—	92.3	4.1	3.6	Stirring 50 rpm, used FCC catalyst 10 wt.%
PP	—	500	1 atm	6	—	82.12	17.76	0.12	
PP	Batch	740	—	—	—	48.8	49.6	1.6	
PS	Semibatch	400	1 atm	7	—	90	6	4	Stirring 20 rpm, used FCC catalyst, cat/poly = 10 w/w
PS	Pressurized batch	425	0.3–1.6 MPa	10	60	97	2.50	0.5	
PS	Batch	500	—	—	150	96.7	3.27	0	Used Zn catalyst, cat/poly = 5 w/w
PS	Batch	581	—	—	—	89.5	9.9	0.6	64.9 wt.% of Liquid- compressed styrene

and other chemical products. The formation of tar during gasification can be reduced via application of olivine as the bed material [73, 82, 83].

5.4. Char and Gaseous Products. The pyrolysis gas produced mainly consists of methane, hydrogen, ethane, propene, propane, and butane. The gas produced is a function of the feedstock material used and the process parameters. Carbon dioxide (CO_2) and carbon monoxide (CO) are produced when the feedstock contains PET material while the hydrogen chloride gas is produced as an additional gas if PVC is part of the feedstock [84]. The composition of the gas influences the calorific value of pyrolysis gas and, hence, its application [6, 16]. The pyrolysis gas has a potential internal use as a source of energy for the pyrolysis plant process. Additionally, during production of polyolefin, the pyrolysis gas is feasible after extracting ethene and propane gas components [81, 85]. Research by Reference [6] provided a summary of pyrolysis studies using various feedstock materials, process parameters, and product yields.

Solid residue or char produced during pyrolysis majorly consisted of volatile matter and carbon with low levels of moisture and ash. Its calorific value was estimated to be 18.84 MJ/kg, thus suitable for use as a fuel, e.g., in combustion with coal. Upgraded chars are used in heavy metal adsorption from industrial wastewater and toxic gases. Other uses include the energy source for boilers and feedstock for activated carbon [81].

6. Design and Construction of Plastic Pyrolysis Plants

This study examined the plastic industry and plastic waste management globally and recommends the development of the waste-to-oil pyrolysis plant as a solution to the plastic waste disposal challenges. This study involved data collection through document analysis and review, interviews, and questionnaires. The quantity of plastics available was estimated for the market using data on production, importation, usage, and recycling. The specification of the pyrolysis plant equipment was done through design analysis with mass balance and energy balance.

The design was realized via the application of techniques like mass and energy balances, financial and economic analyses, and use of design software. The energy and mass balance equations were used to determine the amount of input, throughput, and output per unit cycle of production.

6.1. Design Overview. The main raw material for the pyrolysis plant is a mixture of plastic wastes that are consumed in different products. These include PVC, HDPE, LDPE, PS, PP, PET, and PE that are appropriate for liquid oil production due to their high volatile matter content. The condition parameters (catalysts, pressure, residence time, temperature, and the heat transfer from heat source) determine the quality and quantity of the oil produced. The order of the steps is as follows: crushing of the plastic waste in the crushing machine, heating in the reactor, condensation in the condenser, acid removal, and, finally, distillation in the fractionating column to separate the oil mixtures. Figure 4 below shows the overall process flow diagram.

Figure 4 is a flow diagram showing the main elements of a proposed pyrolysis plant. These parts are the crushing unit and area, reactor, char remover, condenser, fractionating column, and fuel storage vessels.

6.2. Mass and Energy Balances. The amount of output expected from a specific input of the raw material and throughput for the plant was estimated using the general standard assumptions that have been developed and applied in several functional pyrolysis plants and from pyrolysis of plastic waste experiments that have given close results. The assumptions include the percentages of the reactor products at specified conditions of an average temperature of 470°C. Similar reactor conditions were selected for this design, so the mass and energy balance assumptions were directly applied. Table 4 gives the thermal and catalytic pyrolysis yields that were adopted in the design.

From Table 4, it is noted that thermal pyrolysis yields more char compared to catalytic pyrolysis. On the other hand, catalytic pyrolysis yields more liquid fuel than thermal pyrolysis. The average gas production is slightly higher in thermal pyrolysis compared to catalytic pyrolysis.

For thermal pyrolysis, the reactor products from the input are as follows: some small percentage of the raw material, i.e., about 0.053%, is lost at the reactor mainly as moisture content which can be recovered as water. For the catalyst to be used, an estimated mass fraction of 0.023 of the raw material masses at the reactor is used for efficient functioning. At the reactor, 1 kg requires 844 W for complete thermal decomposition per hour. Though the required power input is high, more power is produced at the end of the reaction, which is estimated at 9500 W/kg/h. Upon application of the above mass and energy balance assumptions, the heating value of the gas produced is 50 MJ/h, and the heating value of the crude liquid is expected to be 46 MJ/h [54].

6.3. Reactor Design. The value of plastic pyrolysis products is influenced by the feedstock composition and the reactor technologies applied. All pyrolysis reactors have their pros and cons too, but the choice is guided by the required product and desired flexibility for handling feedstock variations. The two very important factors in reactor design and selection are heat and mass transfer efficiency [33].

The different types of reactors are batch, semibatch, fixed bed, and fluidized bed reactors, hence the need to do analysis to identify the best reactor choice from the many different types of reactors. The batch reactor is a closed system with no entry or exit of reactants and products during the processing time. With time, this reactor can achieve a high yield and has been proven to be the most reliable, but the system is labor intensive; hence, the labor cost is high and the whole process is expensive. The semibatch reactor provides flexibility in the addition of reactants and the removal of process products [16]. The products can be removed and the reactants added simultaneously while using this kind of reactor. Even though it provides flexibility, this reactor has a high operation cost, making it unfriendly especially for large-scale applications. The fixed bed reactor has catalysts broken down into pellets and packed into the bed. The main limitation of this reactor is that it does not provide enough surface area for the reactants to assess the catalyst; thus, it is usually not preferred. This method is rarely used. The fluidized bed reactor, on the other hand, provides for solutions to all the

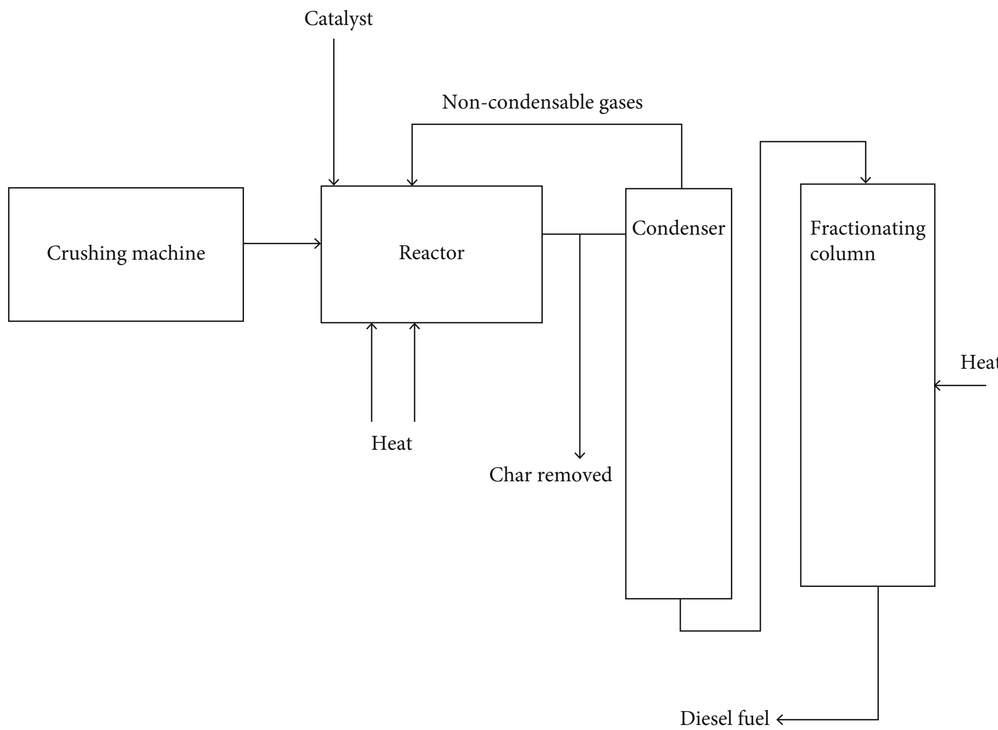

Figure 4: Overall process flow diagram.

Table 4: Thermal and catalytic pyrolysis yields [86].

Thermal pyrolysis		Catalytic pyrolysis	
Char	2–13%	Char	5–10%
Liquid	77–90%	Liquid	80–90%
Gas	8–10%	Gas	5–10%

shortcomings of the other reactors. In this reactor, the catalyst is shred into pellets and packed in the reactor bed. A fluidizing gas is passed through the bed carrying the catalyst particles in a fluid state. This provides better access to the catalyst, as it is well mixed with the fluid, and there is a large surface area for the reaction to take place, hence a higher efficiency and output rate. This is the most preferred reactor because less heat is required, and the addition of feedstock is frequently minimized keeping the labor cost and, therefore, the operation cost low [16].

The most common reactors for plastic pyrolysis are fixed bed/bath reactors, screw kilns, rotary kilns, vacuum bed, and fluidized bed reactors. The type of the reactor selected influences the selection of the heating temperature and heat rates which effectively influence the product yield, composition of the pyrolysis oil, and composition of the pyrolysis gas produced [38]. Important parameters in the design of a plastic pyrolysis plant are the operating temperature based on the material and process, the heat rate, the residence time of materials in the reactors, and the products produced which influence their properties [16, 27].

6.4. Cost-Benefit Analysis. The economic and financial feasibility was done through comparison of the total costs involved in the production process with expected profits. The capital costs included equipment, piping, electrical, direct installation cost, instrumentation and controls, site preparation, setup, and engineering costs. The net present value (NPV) method was used to evaluate the feasibility of the project. Positive NPV will prove profitability while a negative one means that the project will only lead to losses. The formula for calculating NPV is as follows: $\mathrm{NPV} = \sum_{t=1}^{T}(C_t/(1+r)^t) - C_0$, where C_t is the net cash flow during period t , C_0 is the total initial investment cost, r is the discount ratio, and t is the number of time periods.

6.5. Limiting Conditions. It was not possible to access all plastic manufacturers and dealers for the generation of accurate and detailed data. Data used for the evaluation, like for the economic analysis, was the estimated value and not exact. The exact value keeps varying, and thus, average values were used; hence, the obtained results may not be quite accurate. However, available and accessible accurate values were used to improve on the accuracy and reliability. Some information was treated as confidential in some facilities visited.

6.6. Design Principles and Considerations. The pyrolysis system design must take into account four main steps or stages of the process of pyrolysis. These critical steps are (1) even heating of the plastic to reduce the thermal gradient; (2) removal of oxygen from the pyrolysis reactor or chamber; (3) effective control of the char to avoid solidification which converts it to an insulator, thus reducing the heat transfer to the plastic feedstock; and (4) controlled condensation and

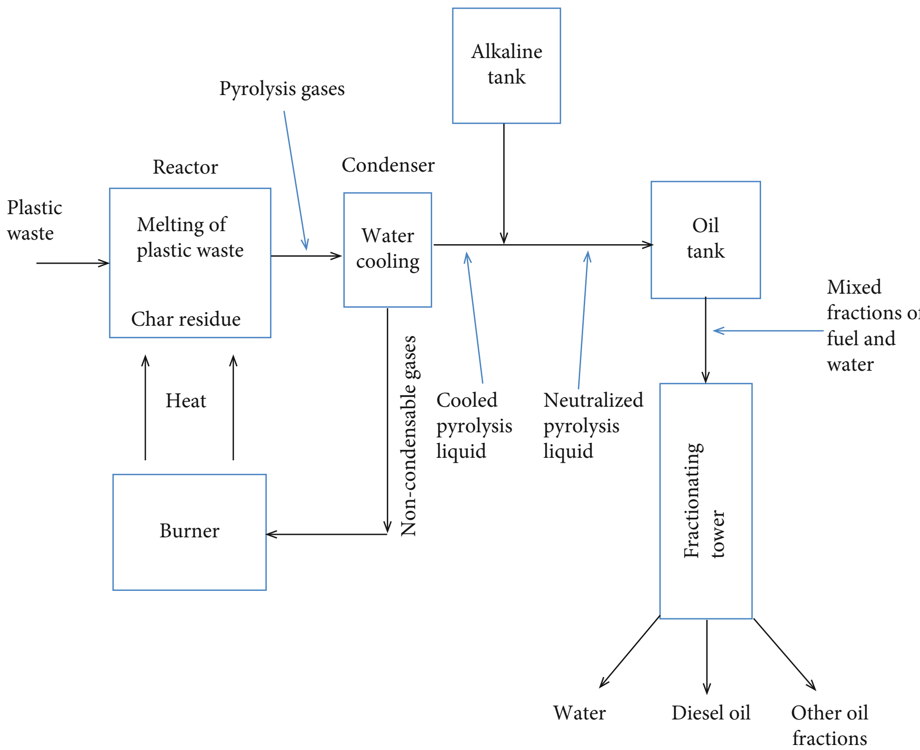

Figure 5: Plastic pyrolysis design flow diagram (authors' conceptualization).

fractionation of the pyrolysis to produce a good quality in terms of composition and consistency [16].

6.7. Pyrolysis Process Design. The comprehensive conversion process of the plastic waste to fuel is demonstrated in the process flow diagram in Figure 5. The most fundamental elements in the process of pyrolysis are the source of heat, reactor condenser, and distillation unit. The input and output vary according to the capacity of the plant selected. To maximize on the plant capacities, several units could be used within the same production line.

From Figure 5, it is noted that water, diesel, and other oils are the main products of the fractionating chamber. The main parts of the system are the heat source, the reactor, the condenser, the oil storage tank, and the fractionating chamber.

6.8. Choice of Reactor. The reactor chamber is heated indirectly by the flow of hot air from the burner. Its temperature is regulated via the controller which operates a valve to allow more hot air or less, depending on the operating temperature. Uniform heating is, thus, achieved at the reactor. The rotating mixer ensures that all of the plastic material is heated evenly. The reactor is illustrated in Figure 6.

Figure 6 shows the reactor and its accessories, which include the controller and mixer. The reactor is connected to the condenser in the assembly.

The two types of pyrolysis-processing methods are continuous and discontinuous cycles. The discontinuous processing uses a batch reactor while the continuous reactors are used for the continuous processing.

6.9. Safety Considerations. The best material for boiler and pressure vessels is carbon steel (material 516 gr 70) as they can withstand high temperatures and pressures without cracking. This material has high tensile and yield strengths that are suitable for the reactor design. Tensile strength = ($510 - 610$) N/mm^2, and yield stress per min = $335\ N/mm^2$.

Reactors have huge differences in terms of design and manufacturing but more so on safety. Table 5 shows the batch reactor design comparison. The dish-end batch design was selected due to its ability to withstand higher pressures, up to 7 bars, thus reducing chances of accidents.

From Table 5, it is noted that batch reactors available in the market have capacities ranging from 5 tonnes to 15 tonnes per batch. To achieve higher input-output capacities, a parallel arrangement of four batch reactors was used. Four reactors were used for the design due to constraints of the initial cost of the plant, or else, more units would have been used. The plant layout with the reactors shown in Figure 7 is used in the design.

Figure 7 shows the batch process option with 4 reactors, one fractionating column, and two condensers.

6.10. Reactor Mass Balance. The mass balance in the reactor is demonstrated in Figure 8. The mass entering the reactor and total mass leaving the reactor should be balanced. mpw is the mass of plastic waste, in tonnes;mf is the mass of pyrolysis oil, in tonnes; mc is the mass of char, in tonnes; andmg is the mass of pyrolysis gas, in tonnes.

From Figure 8, the mass balance expression is shown as follows:

$$\text{mass in} = \text{mass out}, \text{mpw} = \text{mf} + \text{mc} + \text{mg} \tag{1}$$

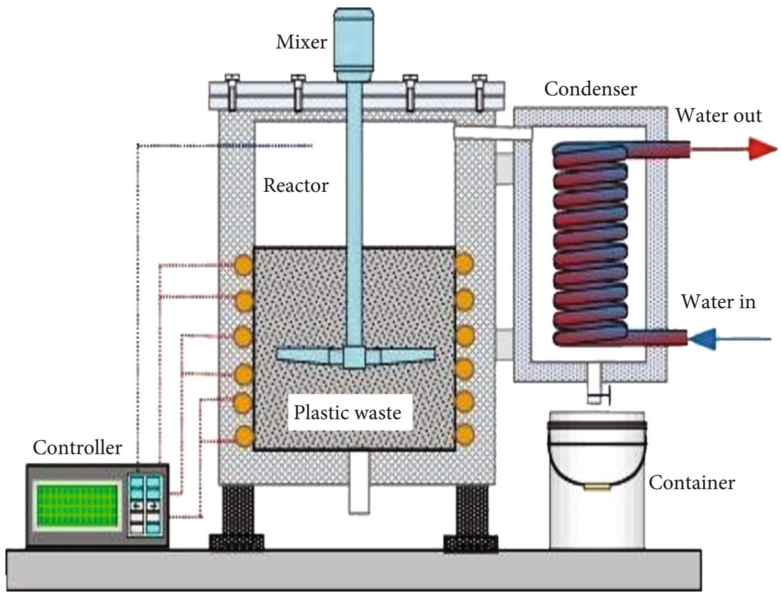

Figure 6: Internal view of pyrolysis reactor.

Table 5: Comparison of reactor designs.

Flat-end batch pyrolysis reactor	Dish-end batch pyrolysis reactor
Withstands 1–2 bars of pressure	Withstands close to 7 bars
Leaks faster, less reactor life	More reactor life
Cheaper	More expensive

The assumptions made in the mass balance are that there are no leakages and that measurements are done accurately.

$$60\,\mathrm{mf} + \mathrm{mc} + \mathrm{mg} \tag{2}$$

6.11. Comparison of Thermal and Catalytic Pyrolysis Processes. From the calculations of the mass balance for both thermal and catalytic depolymerization processes, the two can be compared according to the outputs expected and by using the lower limits of the expected outputs. A further comparison of thermal and catalytic processes is provided in Table 6 below.

From Table 6, it is noted that catalytic pyrolysis gives a higher oil yield than thermal pyrolysis. Thermal pyrolysis has a higher yield of noncondensable gases compared to catalytic pyrolysis. The solid deposit in the form of char is almost the same for the catalytic and thermal pyrolysis processes.

6.12. Condenser. The condenser serves mainly to cool down the vapors from the pyrolysis reactor. Two condenser configurations, i.e. vertical and horizontal, are considered. The main design parameters are the pipe length, pipe diameter, the number of tubes, cooling area, and cooling method applied. Figure 9 shows the side and front views of the condenser [87].

Figure 9 shows the main elements of the pyrolysis plant condenser, i.e., the vapor inlet, the cooling water inlet and outlet, and the condensate outlet.

6.13. Acid Removal. The pyrolysis oil formed may contain acidic contaminants, such as hydrochloric acid and benzoic acid from atomic constituents of PVC and PET, respectively. This is undesirable as the acid corrodes the plant parts and reduces the quality of oil; hence, a neutralizing mechanism was provided. An alkaline solution plastic tank was installed from which a dosing pump delivers the alkaline solution into the pyrolysis oil line. The pump is turned on once the oil flow to the distiller is initiated [1].

6.14. Oil Distiller. The pyrolysis oil has a wide range of boiling points. It is passed through the fractionating column in the oil distiller to obtain useful liquid and gas fractions such as diesel and gasoline. Main control variables are the temperature change in the distillation column, pressure, and reflux ratio of the product oil. The distillation column is demonstrated in Figure 10.

From Figure 10, it is noted that the main parts of a distiller are the distillation column, the condenser, the reflux drum, and the reboiler.

6.15. Cooling Tower. The hot water from the condensers and the oil distiller is cooled down in the cooling tower. The main design parameters for the cooling tower are the cooling range, wet bulb temperature, mass flow rate of the water, dry bulb temperature, air velocity through the tower, atmospheric pressure, and packing mechanism. Since there are losses due to evaporation, drift, and blowdown, makeup water may be required to maintain the water level in the cooling tower basin [1].

6.16. Plant-Processing Method. The research considered both thermal and catalytic polymerizations to identify the best option. From the thermal- and catalytic-processing

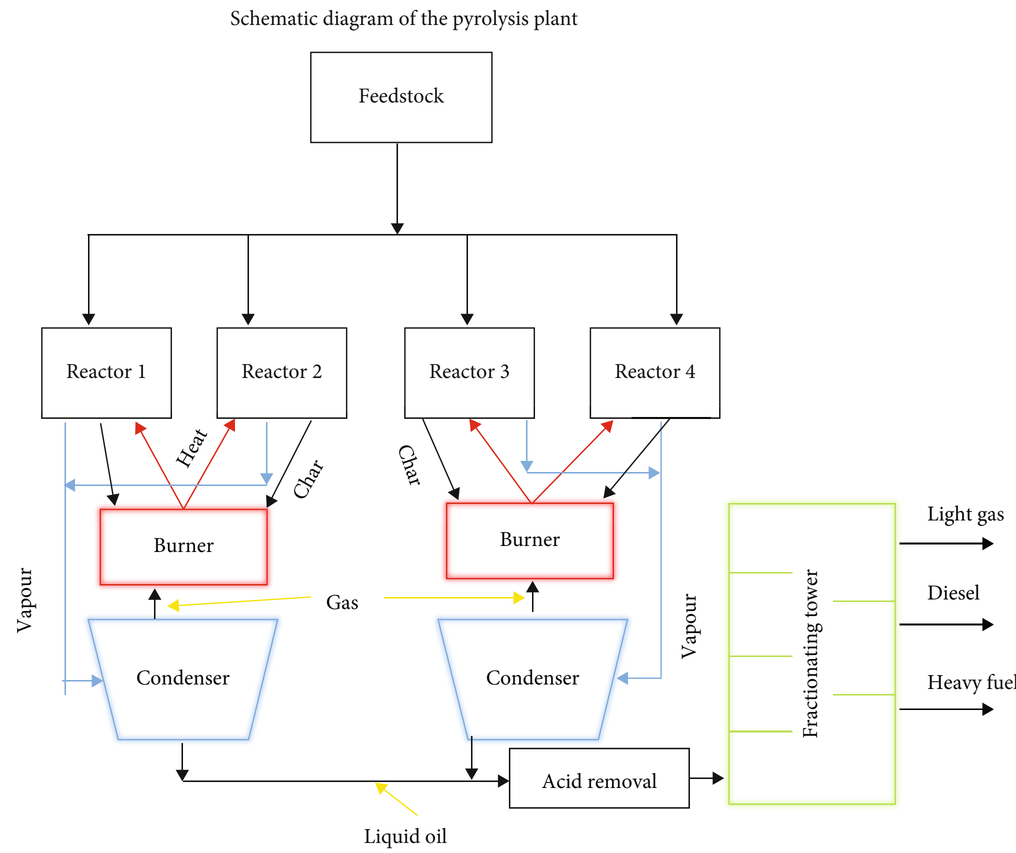

Figure 7: Four reactors arranged in parallel.

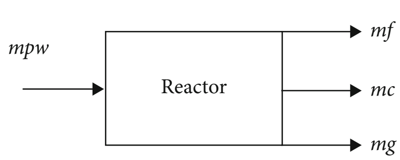

Figure 8: Mass balance for the reactor.

comparison, the catalytic process was found to produce more oil than the thermal process by about 3% [88, 89], but high expenses have to be incurred on the catalyst. Thermal pyrolyzing yields more gas and char compared to catalytic pyrolysis. In the literature review, it is evident that for the same amount of input, catalytic pyrolysis consumes 40% less power than thermal pyrolysis at the reaction stage, but the catalysts used are very expensive, accounting for about 65% of total operating costs [86, 88].

Due to the factors considered, thermal polymerization was selected for this design. With thermal polymerization, the oil product was expected to range from 46.2 to 54 tonnes per day, gases were expected to range from 4.8 to 6 tonnes per day, and the char produced was expected to range from 1.2 to 7.8 tonnes per day. The design provided for the channeling back of the char and gases produced to the burner for combustion to provide energy that is consumed during the process of pyrolysis. The burner was used to provide heat for melting the material in the reactor that utilized a heavy fraction of oil from the fractionating tower, char, and gases (all products produced from the same process), thus minimizing costs that would be incurred from using entirely continuous energy to run the plant. The specifications of the reactors, condensers, fractionating tower, cooling tower, tanks, pumps, valves, and pipes were done through a simple calculation of flow rates and mass and energy balances. The equipment that had specifications close to those required for the design was selected from manufacturers [28, 48].

6.17. Safety Considerations. Safety is a very important aspect of plant design. Carbon steel (material 516 gr 70) that has high tensile strength and high yield stress was selected for the pipes, reactor, and valves of the plant to avoid accidents caused due to cracking of the material under high pressures. The dish-end reactor design was selected over the flat-end reactor due to its ability to withstand pressures up to 7 bars, thus eliminating the possibility of explosions in the reactors in cases of pressure rise.

Noncondensable gases from the condenser (methane, ethane, propane, butane, and hydrogen) can be a serious fire risk and should never be allowed to leak to the environment via proper sealing and selection of the right materials and fittings. In the proposed design, the gases were channeled back to the reactor and burned to release energy while the noncombustible gases were flared to release carbon dioxide and water,

Table 6: Thermal depolymerization vs. catalytic depolymerization.

Thermal depolymerization	Catalytic depolymerization
Less liquid fuel produced	More liquid fuel produced
Higher yield of gases and char	Lower yield of gases and char
Generally requires more energy	Less energy required
Gases produced are channeled back to the reactor to boost energy	Catalysts used are very expensive, accounts for 65% of production cost

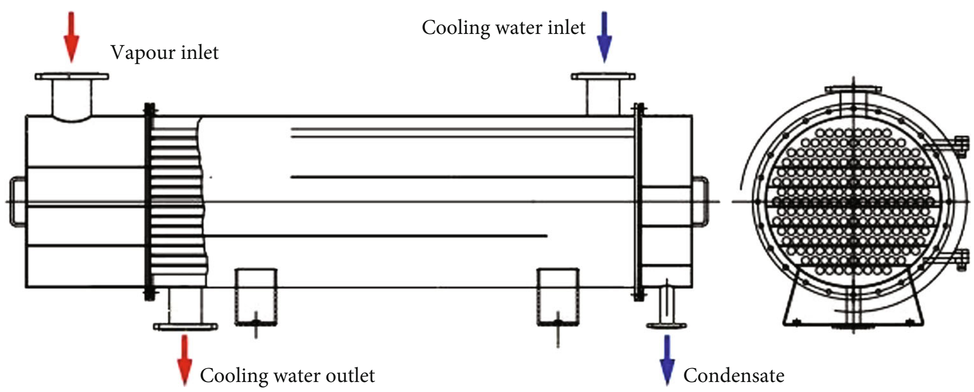

Figure 9: The condenser.

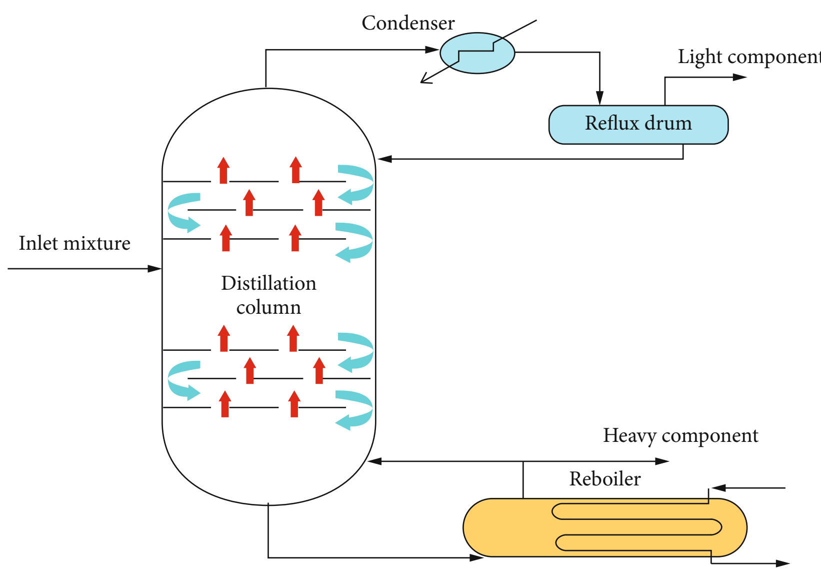

Figure 10: Oil distiller.

which are not toxic substances [59]. Measures applied to guarantee safety of the installation include the following:

(i) Lagging was provided for the burner, reactor, and pipes that carried hot content to avoid burning the workers in case of contact

(ii) The design provided a closed system where no content was released till the end of the processing line after distillation ensuring workers were not exposed to any contaminants throughout the process

(iii) Neutralization of the acidic content in the oil is done immediately after the condensation of the pyrolysis liquid, thus avoiding acids when workers handle the final products directly

7. Challenges and Opportunities of Plastic Recycling

Plastics are cheap, lightweight, and durable and can be easily molded into many different products, shapes, and sizes, hence their wide applications globally, leading to increased production and use. The high level of plastic consumption and related disposal has created serious environmental concerns with about 4% of global oil and gas production being used as a feedstock for plastics and 3–4% being used to provide energy for their manufacture. A significant proportion of plastics is used to make disposable items of packaging and short-lived products that are soon discarded to the environment that is an indication that the current use of plastics is not sustainable [1, 30, 90].

Recycling is one of the most appropriate measures available to minimize the environmental impacts in the plastic industry today. Recycling reduces oil usage, CO_2 emissions, and waste disposal. Other measures include downgauging or product reuse, use of biodegradable materials, and fuel recovery. The quantities of plastics recycled vary widely geographically according to the type of plastic and applications, with plastic recycling being done since the 1970s. More opportunities for recycling are being created via advances in technologies and systems that are applied for the collection, sorting, and processing of used plastics aided by the combined effort of the public, environmental authorities, industry, and governments to ensure that majority of plastic wastes are recycled [91].

A leading challenge in plastic recycling is the recycling of mixed plastic wastes. The main advantage is the ability to recycle a significant proportion of the waste stream through the postconsumer collection of plastics to include a wider variety of materials and pack types. Product design should consider recycling to increase the ease and potential of recycling of plastic products in terms of composition, shape, and size. Studies in the UK in 2007 showed that the amount of packaging in a regular shopping basket cannot be effectively recycled in the range of 21 to 40% even if it is collected. This calls for implementation of policies that promote the application of environmentally friendly design principles by plastic industries to increase recycling performance by increasing the proportion of materials that can be technically and economically collected and recycled [1, 91].

Light plastics like packaging materials are quite problematic during collection and sorting, which is the main reason for most postconsumer recycling schemes targeting rigid packaging. A significant number of recovery facilities cannot handle flexible plastic packaging due to different handling characteristics of rigid packaging. Additionally, the low weight-to-volume ratio of films and plastic bags makes them less economical to invest in in collection and sorting facilities, except for plastic films recycled from sources like secondary packaging, e.g., the shrink-wrap of pallets and boxes and some agricultural films, which is feasible under correct conditions. The solutions to the economical recycling of films and flexible packaging include investment in separate collection, sorting, and processing facilities at recovery facilities that can handle mixed plastic wastes. Successful recycling of mixed plastics requires high-performance sorting to ensure that plastic types are separated to high levels of purity in addition to the development of end markets for each polymer-recycling stream [91].

Rationalizing the diversity of materials to a subset of current usage could dramatically increase the effectiveness of postconsumer packaging recycling. If rigid plastic containers ranging from jars and bottles to trays were all PET, HDPE, and PP, without clear PVC or PS, which are difficult to sort from comingled recyclables, all rigid plastic packaging could be collected and sorted to make recycled resins with very little cross-contamination. Labels and adhesive materials should be collected and used to maximize recycling performance. Sorting/separation within recycling plants should be improved to increase the potential for recycling and better eco-efficiency by reducing waste fractions, water, and energy use with the recycling objective being to maximize the volume and quality of recycled products [91].

8. Results and Discussion

Plastics are popular and have found a wide range of applications because of the lightweight; they do not rust, do not rot, are cheap, are reusable, and have significant socioeconomic positive impact. However, plastics are nonbiodegradable, and huge quantities of plastic wastes have become a nuisance to the environment. Sustainable use of plastic wastes should encourage reuse and recycling [92, 93].

Plastics are important, widely used materials used to make products having a wide range of mechanical and chemical properties suitable for application in many industries like packaging, automotive, and electronics. However, use of plastics is a danger to the environment mainly because they are generally nondegradable leading to accumulation in waste landfills and natural habitats including seas. Recycling, including use in the production of pyrolysis oil, will lead to reduced CO_2 emissions, reduced energy consumption, and waste disposal with the main challenge being waste collection and transport to recycling facilities that requires policy interventions. Research and technology into new recycling solutions should be undertaken to increase the level of recycling.

Huge quantities of plastic wastes can be can be used as feedstock to produce fossil fuel substitutes. Plastic pyrolysis plants have been set up in a number of countries globally to convert waste plastic to hydrocarbon fuel, which may be a cheaper partial substitute of the petroleum oil. Production of the pyrolysis oil from plastic wastes is ecologically and economically superior to many other options since it addresses the environmental pollution and partially addresses the challenge of fossil fuel reserve depletion by reducing demand of primary oil by acting as a substitute feedstock in the production of lubricants and other oil products [34, 94]. The overall effect of waste plastic pyrolysis is the reduction in hazardous plastic waste as well as reduction in the import bill for oil-importing countries.

The challenges facing plastic pyrolysis as a process for oil production are the existence of limited standards for the regulation of the process and products of recycled plastics and the development more efficient and cheaper pyrolysis technologies. The economic viability of plastic pyrolysis is dependent on the design and development of suitable reactors to suit the wide range of plastic waste feedstock with varying process requirements and product output, and a reduction in the capital investment and cost of operation and maintenance [1, 90].

Plastic production has been growing steadily since the first production in the 1950s to date. Due to their short life cycle, there is a high rate of waste generation, hence the need to recycle. All the more as only about 15% of plastic wastes are recycled globally. The total amount of plastic waste that is disposed to the environment each year in Kenya was estimated at 221,000 tonnes with a low recycling rate of 15% of the total plastic material consumed yearly [25]. The low rates of recycling indicated a gap in the plastic market that has not yet been fully ventured into, thus the massive pollution caused by the waste plastic material. Development of the pyrolysis plant for the Kenya plastic market was therefore a viable solution due to its ability to process a large amount of waste. Large amounts of the waste and high plastic consumption were also an indicator of availability and reliability of the raw material (plastic waste) for the pyrolysis plant. Studies have shown that thermal pyrolysis yields more char compared to catalytic pyrolysis. On the other hand, catalytic pyrolysis yields more liquid fuel than thermal pyrolysis. The average gas production is slightly higher in thermal pyrolysis compared to catalytic pyrolysis. Overall, the difference in the output is close enough in terms of the product output, and the process plant designer would rather analyze other factors like the cost in the process selection, although catalytic pyrolysis is superior in terms of solid remnants that should be landfilled [1, 30, 89].

Not all stakeholders are positive about the rationale of converting plastics to fuel. Some environmentalists have argued that widespread adoption of plastics to fuel could slow down efforts to develop sustainable alternatives to fossil fuel which will work against the effort to realize zero emissions by 2050 [53]. Further analysis shows that pyrolysis as a recycling measure has a lower carbon footprint incineration even though it has a significant energy potential [5]. A well-established plastic waste collection system is necessary for the proper success of plastic waste recycling. Through continues awareness, the public will support the recycling effort as contributors and users of the plastic wastes and pyrolysis oil. The government should provide a conducive environment for plastic waste recycling through policy and legal measures as well as provision of economic and financial incentives.

For developing countries like Kenya, Nairobi City has the highest amount of plastic generation, collection, and recovery, with just 45% of plastics recovered. Kisumu City has the lowest waste collection and recovery rates at 20% and 8%, respectively, making it the most plastic-littered city in Kenya. Nairobi and other cities face the challenge of plastic waste disposal because of weak policies and the failure to adhere to the guidelines on solid waste management by the stakeholders. There is the need to develop a policy framework that promotes plastic waste recycling through education and sensitization, creating a market for recycled products, and changing people's attitudes to embrace recycling. The government should promote the recycling industry through legislation, funding, and other forms of support. These will increase the levels of recycling that is below the global average of 15%.

Pyrolysis is an important process due to the increasing quantities of plastic waste and the increasing percentage composition of thermosetting plastics that need to be recycled. However, pyrolysis also produces toxic byproducts from the pyrolysis of some plastics like polyvinyl chloride (PVC). Additionally, the pyrolysis oil produced from plastic pyrolysis has inferior properties like a high sulphur content which is undesirable as it is harmful to the environment. The oil has a relatively lower flash point generally ranging from 10 to 40°C compared to about 50°C for commercial-grade diesel, which is an indicator of high volatility and, hence, is risky compared to conventional fossil fuels. This can, however, be improved by blending with commercial-grade fuels and the installation of sulphur systems, especially for industrial applications. Since the waste plastic pyrolysis oil has a higher sulphur content compared to conventional diesel, kerosene, light fuel, oil and gasoline, it may not be the best direct substitute where these fuels are used. However, its sulphur content is lower compared to that of heavy fuel oil and furnace oil. This implies that, as far as emission and environmental pollution is concerned, the waste plastic pyrolysis oil can be a better substitute for diesel engine power plants running on HFO and industrial processes using furnace oil. According to [95], proposed improvements to improve the quality of the pyrolysis oil include the inclusion of hydrogen chloride and sulphur dioxide scrubbers, for the removal of significant impurities like the HCl vapor and sulphur dioxide from the recovered oil. Blending is also recommended in varying proportions with renewable fuels like biodiesel, ethanol, and, to limited proportions, conventional fossil fuels to improve properties as well as reduce the carbon footprint of the fuels.

Economically, the pyrolysis oil can replace the conventional diesel oil in terms of the engine performance and energy output if the price of the pyrolysis oil is less than 85% of the price of conventional diesel [49]. According to [50], crude oil prices above $65 per barrel are necessary to justify commercial investment in waste plastic to fuel without a premium, but with a green premium, recycling waste plastic to fuel is still viable at prices below $65 per barrel. A diesel engine was noted to give better performance when using a fuel that contains pyrolysis oil of up to 30%, and it may perform well with a maximum of up to 50% of the waste plastic oil blended into conventional diesel. In another study by [51], it was observed that an engine has stable performance with the brake thermal efficiency being comparable to that of conventional diesel, and the value of the brake thermal efficiency is higher with the pyrolysis oil by up to about 80% of the engine load. However, the engine emissions were notably higher with the pyrolysis oil compared to the conventional diesel [51]. To improve the efficiency and further reduce the cost of the plastic waste pyrolysis process, a proposal is made with regard to the process improvement to reduce energy use and generate power from the pyrolysis gas and other combustible products for plant use and to export the excess power to the grid to earn extra revenue for the recycling facility and substitute generation from other fossil fuels. Melting plastics at higher pressure zones may reduce the fuel-burning temperature and, hence, energy consumption through a high-pressure zone so that the fuel-burning temperature can be decreased and the efficiency improved, as it leads to a reduced boiling point. Increased applications and adoption of pyrolysis products will lead to increased investment and, hence, economies of scale leading to further process efficiencies and cost reduction, making pyrolysis a more profitable and attractive venture. Pyrolysis liquids can be used as feedstock to substitute the fresh oil in the manufacture of plastics, lubricants, industrial fuels, power plant oil, and industrial fuel. This calls for policy incentives and research into efficient pyrolysis technologies [1, 5, 42, 95].

The oil produced from plastic wastes generally has a higher sulphur content compared to the conventional fuel oil. This requires the users of the pyrolysis oil to be equipped with environment protection devices to scrub the flue gases produced, which raises concerns from users and environmentalists. Sulphur causes emissions of oxides to the environment that can increase cases of acid rain. The pyrolysis oil has a higher sulphur content compared to conventional gasoline, kerosene, and commercial-grade diesel. In a typical case, the sulphur content of the waste pyrolysis oil (WPPO) was 0.246% compared to the 0.15% content for diesel oil and 0.014% for gasoline. When mixed plastics are used, typical studies showed a 4.8% sulphur content for thermal pyrolysis and 4.36% for the catalytic pyrolysis liquid fuel from mixed waste plastics [6, 96].

The main products of plastic pyrolysis are the pyrolysis oil, a hydrocarbon-rich gas, with a heating value of 25–45 MJ/kg that makes it ideal for process energy recovery and char. Hence, the pyrolysis gas can be fed back to the process to extract the energy for the process-heating purpose which substantially reduces the reliance on external heating sources.

From the literature review, it was deduced that the fuel produced from this process is of high quality with properties like diesel oil (heating value of about 45 MJ/kg, density of 0.77–0.86 g/cm^3, and cetane number 40–60) and needs little modifications like fuel injection timing in diesel engines. The pyrolysis oil can be used as the transport fuel. Other feasible applications are gas turbine fuels, diesel generators, aviation industry fuel, and jet propulsion. When blended with diesel in suitable ratios, the pyrolysis oil can be suitable for various applications like fuel for boiler furnaces, lubrication oil production, waxes, and plastic feedstock production. Waste plastic pyrolysis offers a more sustainable solution to plastic waste pollution and reduced use of virgin oil. The economic analysis of this project has proven it to be highly profitable, returning the investment cost after a period of five years. The increased investment and use of the waste plastic pyrolysis oil will reduce the demand for fresh fossil fuels, while blending with renewable fuels for use in power generation will make plastic waste pyrolysis a significant player in the energy transition to low-carbon power generation and energy consumption [30].

With an increase in the global production and consumption of plastics, and less than 20 percent of plastics recycled globally, the plastic waste is increasing and mismanaged. The impacts of plastic production, use, and disposal on the environment and people create risks and opportunities for investors through different sectors and companies that are a part of the plastic value chain. This report highlights the global challenge for plastics, as well as some potential solutions.

Global plastic production and consumption have grown by over 20 times since the 1960s. About 40% of plastics produced are for packaging with 95% of them for single-use. The production and consumption of plastics continue to grow amid an inefficient global waste management system, with less than a fifth of plastic wastes being recycled. The various stages of the plastic value chain create significant greenhouse gas emissions. It is estimated that greenhouse gas emissions from plastics may account for 10–13% of the entire remaining carbon budget by 2050 within the context of the 1.5°C target of the United Nations Framework Convention on Climate Change Paris Agreement [97].

9. Conclusions

Plastics are cheap, lightweight, and durable and can be easily molded to many different products, shapes, and sizes, hence their wide applications globally leading to increased production and use. Plastic consumption and production have been growing since first production in the 1950s. About 4% of the global oil and gas production is being used as feedstock for plastics, and 3–4% is used to provide energy for their manufacture. The short life cycle of many plastics and their wide use in domestic and industrial applications have led to significant quantities of plastic wastes globally. Plastic demand is high globally, and it continues to grow mainly because of its flexibility and affordability for a wide range of industrial and commercial applications. Many countries and regulatory authorities are calling for the ban of certain categories of plastics while others like Kenya have already banned the manufacture, sale, and use of single-use carrier bags. This has serious socioeconomic impacts like loss of jobs, business opportunities, and livelihoods, although it brings environmental benefits related to reduced plastic waste pollution. Plastic waste recycling can be used as a feasible solution to the huge plastic waste pollution. There are many strategies and options for plastic recycling classified as primary, secondary, tertiary, and quaternary recycling techniques. There are four main avenues available for plastic solid waste treatment, namely, reextrusion as a primary treatment, mechanical treatment as secondary measures, chemical treatment as a tertiary measure, and energy recovery as a quaternary measure. Various operations involved in plastic recycling include the separation, sorting, and cleaning of the wastes. The main challenges facing plastic recycling include high collection and transport costs, high electricity bills, and feedstock with a wide variation of quality and properties due to different plastic types.

The common methods used in plastic disposal are incineration and landfilling, while plastic pyrolysis can be applied to produce useful oil and other products from plastic wastes. Although some countries have banned the production and sale of some plastics like single-use plastic bags, the quantities of waste plastics remain high, hence the need to promote alternative methods of plastic recycling. This study proved the significance of plastic waste recycling as a means of combating greenhouse gas emissions from the energy sector by using waste plastic as a source of an alternative high-value fossil fuel. The study showed that plastic pyrolysis is a cleaner, efficient, technical, and commercial way of plastic waste disposal, which besides solving the environmental crisis from solid waste disposal will also generate fuel revenue and savings by producing an alternative fossil fuel which will reduce the demand for primary fossil fuels and, hence, the related environmental costs and resource depletion. The best and most sustainable solution to plastic pollution is recycling. There are various methods of plastic recycling like primary, secondary, tertiary, and quaternary recycling.

Plastic pyrolysis is an attractive option for the plastic waste as many authorities and countries globally call for a ban of several plastic categories from the market due to failure of the conventional methods of plastic waste control to address environmental pollution due to plastic wastes. The process, however, still faces a number of limitations particularly with respect to the collection, separation, sorting, and cleaning operations and the high cost of power and transportation.

Pyrolysis generally produces fewer toxic products as long the process is well designed and the process conditions controlled appropriately. However, the process has notable issues surrounding some toxic byproducts from plastics like polyvinyl chloride, which requires proper feedstock selection. Another challenge is that the liquid fuel from plastic pyrolysis is not a perfect fit for many engineered applications mainly because of the relatively high sulphur content, which can be addressed though further treatment and blending with commercial-grade oil products. Other than liquid pyrolysis oil, a hydrocarbon-rich gas, is produced, having a heating value of 25–45 MJ/kg, which makes it ideal for process energy recovery. Hence, the pyrolysis gas can be fed back to the process to extract the energy for the process-heating purpose that substantially reduces the reliance on external heating sources. A leading challenge in plastic recycling is the recycling of mixed plastic wastes. The main advantage is the ability to recycle a significant proportion of the waste stream through the postconsumer collection of plastics to include a wider variety of materials and pack types. More opportunities for recycling are being created via advances in technologies and systems that are applied for the collection, sorting, and processing of used plastics aided by the combined effort of the public, environmental authorities, industry, and governments to ensure that the majority of plastic wastes are recycled.

10. Recommendations

Furthermore, this study recommends investigation into the best waste-to-energy conversion process for a cost-effective waste plastic recycling and performance of various biodiesels and waste plastic pyrolysis oils to increase the green value of plastic pyrolysis oil production. Additionally, the study recommends plastic waste liquefaction as another recycling pathway for the enhanced application of plastic wastes in the production of products like naphtha by converting polymers to liquid chemical products. Research into the economic and technical feasibilities of bioplastics is recommended as a strategy of improving plastic recycling.

Abbreviations

CAGR: Compound annual growth rate (CAGR)
ELV: End-of-life vehicle
GWP: Global warming potential
HFO: Heavy fuel oil
PET: Polyethylene
POPs: Persistent organic pollutants
PSW: Plastic solid waste
TEU: Total energy use
WEEE: Waste electrical and electronic equipment
WPPO: Waste plastic pyrolysis oil.

Data Availability

The authors will provide any data used upon a written request to the corresponding author.

Additional Points

Article Highlights. (i) Plastics are cheap, lightweight, and durable and can be easily molded into many different products, shapes, and sizes, hence their wide applications globally, leading to increased production and use. (ii) The global plastic production has tripled since the 1950s causing challenges in waste plastic disposal. (iii) About 4% of global oil and gas production is being used as feedstock for plastics, and 3–4% is used to provide energy for their manufacture. (iv) Incineration and landfilling are the most prevalent forms of plastic disposal. (v) Through plastic pyrolysis, alternative fuel can be produced which can reduce demand on virgin oil and create a sustainable disposal pathway for waste plastics.

Disclosure

The authors have the authority to publish the research work in any publication.

Conflicts of Interest

The authors declare that they have no potential conflict of interest in this research.

Authors' Contributions

It was the responsibility of the first author to conceptualize and draft the manuscript. The second author provided guidance, proof reading, and editorial services in addition to further theoretical and technical input.

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