FUEL FROM PLASTIC WASTES FOR SUSTAINABLE ENERGY TRANSITION

Moses Jeremiah Barasa Kabeyi
22064693@dut4life.ac.za
Industrial Engineering Department, Durban University of Technology, Durban South Africa
Oludolapo Akanni Olanrewaju
oludolapoo@dut.ac.za
Industrial Engineering Department, Durban University of Technology, Durban South Africa

ABSTRACT

Plastics are essentially made up from fossil fuels and can therefore be reverted to oil. Pyrolysis involves the conversion of plastic wastes to fuel by thermally degrading long chain polymers into small complex molecules in the absence of oxygen. The objective of this study was to minimize plastic pollution and overdependence on fossil fuels by conversion of waste plastics to fuel. This study proposed a plastic oil pyrolysis plant as a solution to the challenges of plastic pollution and ever-growing demand for fossil fuels. The pyrolysis process is advantageous because presorting is not required, and the plastic waste can be directly fed and does not require pretreatment prior to the process. The plastics available for recycling currently used in the model is 15.83% of available quantity. The projected production is 29,826 liters per day. The preliminary evaluation showed that the pyrolysis economically viable project since the fuel obtained from the process is cheaper as compared to the convectional diesel as seen in the current market prices retails for about Ksh80 (US$ 0.8).

Abstract: Plastic recycling: waste to energy; plastic pyrolysis; pyrolysis oil.

1.0. INTRODUCTION

Over 3000 million tons of plastics are produced globally accounting for about 8% of world oil production(Oyake-Ombis, 2012). With over one trillion plastic bags production annually, the plastic bags are the most important user or application of plastics globally(Agency, 2018; Al-Salem, Antelava, Constantinou, Manos, & Dutta, 2019). The process of recovering and processing of waste plastics to useful products is called recycling. Plastic recycling reduces dependence on landfill, conserve resources and protect the environment from plastic pollution and greenhouse gas emissions(Al-Salem et al., 2019; Olalo, 2021). Waste plastics can be processed to oil by thermal and catalytic conversion. This is a promising technology that will not only reduce plastic waste pollution, but also reduce the increasing dependence on fossil fuels for energy(Kunwar, Cheng, Chandrashekaran, & Sharma, 2016).

Urbanization has led to massive growth in plastic production globally. Despite the many applications of plastics like packaging, plastics in the recent years they have become a nuisance especially towards the environment, human health, and aquatic life. In 2018, the plastic production was rated at 280,000 tons per annum and a small percentage of only 15.3% is being recycled while the rest ends up in landfills, drainages, and open spaces. There is need to increase the rates of recycling to reduce plastic wastes and other municipal solid wastes (Kabeyi, 2020). The rapid growth in the production of plastics in the world has led to the pollution of the environment, aquatic life and brought about complications in human health. Of the plastics produced, about 50% are disposable and can be reused, recycled or dumped (RU, 2010) and about 50% are used for disposable application. The impacts of plastic wastes in aquatic life include the increased presence of micro plastics which result in breakdown of larger plastic in aquatic ecosystems. They occur in form of spheres, pellets, and fragments. These plastics contain several hazardous chemicals such as thalates, poly-fluorinated chemicals, antimitroxide and brominated flame retardants (Andrews, 2012). Brominated flame polybrominated diphenyl ethers (PBDEs) cause neurotoxic effects towards aquatic microorganisms. Plastics to fuel is an alternative means of plastic waste disposal while still offering fuel for use(Kunwar et al., 2016).

The process used in plastic recycling is pyrolysis which involves degradation of polymeric materials to produce high quality fuel which can be used in diesel engines, boilers, and furnaces. Polyvinylchloride (PVC) and polyethylene terephthalate (PET) are not used for this process since they produce high quantities of acid and low yields of fuel. The aim of this project is to convert plastic waste by heating them under controlled conditions to produce oil like industrial diesel and heavy fuel oil to be used in power plants, furnaces, and boilers. In Nairobi, a city with a population of about 4 million people is only served by one major dumpsite, Dandora dumpsite, which was commissioned in 1977(Rivier, Collignan, Meot, Madoumier, & Sebastian, 2018).

2.0. PLASTIC PYROLYSIS

The process of thermal degradation decomposes plastic materials into three main fractions namely: gas, crude oil, and solid residue. The crude oil from the non-catalytic pyrolysis process is usually composed of higher boiling point hydrocarbons. It is necessary to optimize parameters like the choice of catalysts, design of reactor pyrolysis temperature, as well as plastic-to-catalyst for efficient production of gasoline and diesel grade fuel from plastic wastes. Catalysts lower the energy hence the choice is important for efficient fuel production. Co-pyrolysis of plastics with use of coal or shale oil is known to decrease the viscosity of crude oil and hence improves crude oil(Kunwar et al., 2016). The conversion of plastics to fuels can be done through several processes. These processes include gasification, pyrolysis, plasma process and incineration. Pyrolysis is the process whereby plastic wastes are converted into solid, liquid, or gaseous fuels by thermally degrading long chain polymers into small fewer complex molecules in the absence of oxygen. The major products that results from this process include high calorific gas, high quality oils and carbonized char(Agency, 2018).

Pyrolysis is the process whereby plastic wastes are converted into solid, liquid, or gaseous fuels by thermally degrading long chain polymers into small fewer complex molecules in the absence of oxygen. The major products that result from this process include high calorific gas, high quality oils and carbonized char. The process can produce high amounts of oil of up to 80wt% at moderate temperatures of 500^{0}C (FakhrHoseini & Dastanian, 2013). Pyrolysis is divided into two major groups: thermal and catalytic pyrolysis(Agency, 2018; Riley et al., 2020). Figure 1 below gives a pictorial view of major components of a plastic pyrolysis process.

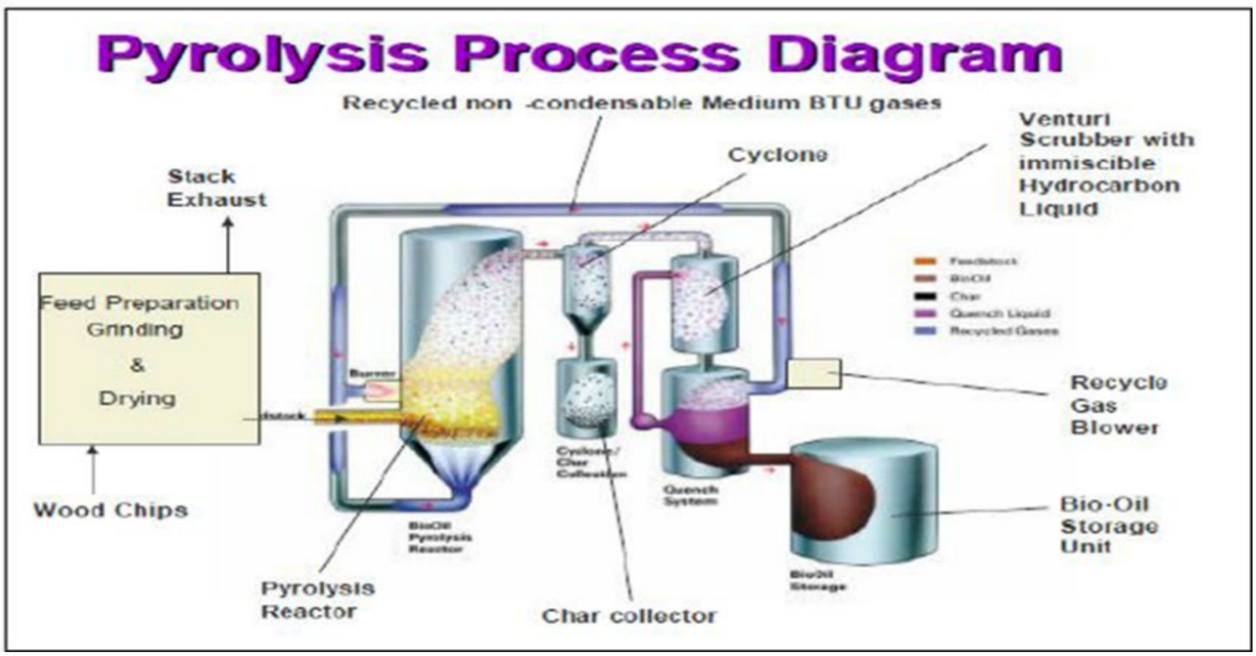

Figure 1: A schematic diagram of the Pyrolysis process

From figure 1 above, it is observed that the main elements of a plastic pyrolysis process are preparation and missing chamber, the reactor, the cyclone with char collector, venturi scrubber and the oil storage unit.

i.) Thermal cracking

Thermal pyrolysis is the process of heating plastic materials in inert conditions. It involves the decomposition of the organic parts of the plastic polymer to obtain liquids and gases which are used for fuels. The process is usually conducted at temperatures between 300^{0}C and 900^{0}C. Thermal pyrolysis requires high temperature which results in low quality which makes the process less fashionable. This occurs because the un catalyzed thermal degradation gives rise to low molecular weight products(Debora Almeida, 2016).

ii.) Catalytic cracking

Catalytic pyrolysis involves the process of heating plastic in inert conditions in the presence of catalysts. It is done at temperatures ranging in between 350^{0}C and 550^{0}C. Catalytic pyrolysis can be applied in the recycling of either pure or mixed plastics. This process yields higher quality of fuel oils as compared to thermal pyrolysis. The use of catalytic pyrolysis promotes decomposition reactions at low temperatures with low energy consumption, reduced costs, faster cracking reactions, increase process selectivity and increased yield of products with high added value. The table 2 below shows the comparison between the catalytic and thermal pyrolysis(Al-Salem et al., 2019).

2.1. Plastic Recycling Globally

Japan being a small, densely populated country faces a major challenge in providing for a population of a huge demand in energy. With about 10 million tons a year of plastic wastes being generated in a year, recycling through pyrolysis has become a primary objective. The main challenge faced by the country is mainly to recycle plastic wastes which are difficult to recycle or have little commercial value. In 2014, 2.75 million tons of plastics, mainly PET and PVC, had to be landfilled or incinerated due to a lack of recycling plant. Sapporo plastic Recycling plant (SPR) is a well-established pyrolysis plant in Japan recycled (*SPR Japan*, 2015)

SPR is a fully commercial plastic liquefaction facility on the island of Hokkaido which was established in 2000. The facility has a capacity of recycling 50 tons of plastic wastes in a day. Through research, they have also learnt to deal with the benzoic acid which is converted to benzene without affecting the potential hydrogen of the oil product. SPR have also developed the Cascade Recycling System, whereby plastics from municipal solid waste stream that can be mixed with residues and rejects from other recycling processes which amount to 40% to 50% of the output. The residue has a high PET and PVC content, but it can be blended with municipal solid waste plastic stream at up to 40wt% without adverse effect on the reactor or the product quality. Over 100,000 tons of plastic has since been recycled **(*SPR Japan*, 2015).** Figure 2 below shows the pyrolysis process with products and by products and their applications.

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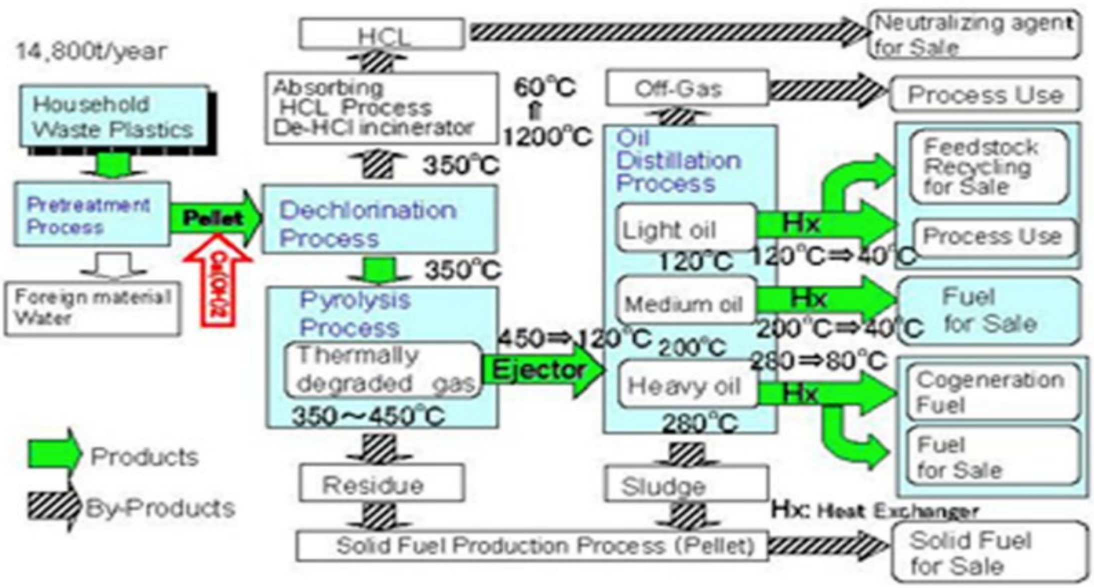

Figure 2: Industrial Waste Plastic to Oil Pyrolysis Plant in India ("Agile Process Chemicals," 2017)

Figure 2 above is an illustration of a process plant with the main stages and processes in the plastic pyrolysis process as well as the main products and by products with their possible applications. The main products 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.

2.2. Plastic Production in Kenya

In Kenya, plastics are mainly produced for packaging of products, manufacturing of household and industrial containers, piping and many more applications. According to the Kenya Association of Manufacturers, there are 176 plastic manufacturing companies worldwide. Below is a tabulation from National Environmental Management Authority (NEMA) showing the percentages of plastic waste generation, collection, recovery, and uncollected waste in the five major towns. In Kenya, most plastics are not collected and disposed of and thus creates a negative environmental and health impacts(Oyake-Ombis, 2012). Table 1 below shows the summary of plastic waste generation and collection for Nairobi.

Table 1: Summary of waste generated, collected, recovered and uncollected in major towns (Author's analysis)

Town	Estimated Plastics Generated (tons/day)	% Waste Collected	% Waste Recovered	% Uncollected Waste

Nairobi	1200	80%	45%	20%
Mombasa	1100	65%	40%	35%
Kisumu	200	20%	8%	80%
Eldoret	300	55%	15%	45%
Nakuru	125	45%	18%	55%

From table 1 above data in table 1, Nairobi generates, collects, and recovers the highest numbers of plastic wastes. This can be attributed since it is highly developed and has better mechanisms of collection and is well organized as compared to other towns. In terms of uncollected waste Nairobi ranks least due to organized waste collection by the county. The figures resulting from the uncollected waste shows that a large majority of the plastic wastes are held up in the landfills.

2.1 Sources of Plastic Waste

Plastic wastes constitute of most wastes in municipal and industrial wastes in cities. Economic growth and production patterns in major cities result in a rapid increase in the generation of plastic wastes in the world. The production is mainly due to PET bottles, plastic shopping bags, plastic packaging and goods using plastics as the major components(El-Newehy, 2016). Figure 3 shows the proportionate contribution of municipal solid waste which include plastic wastes.

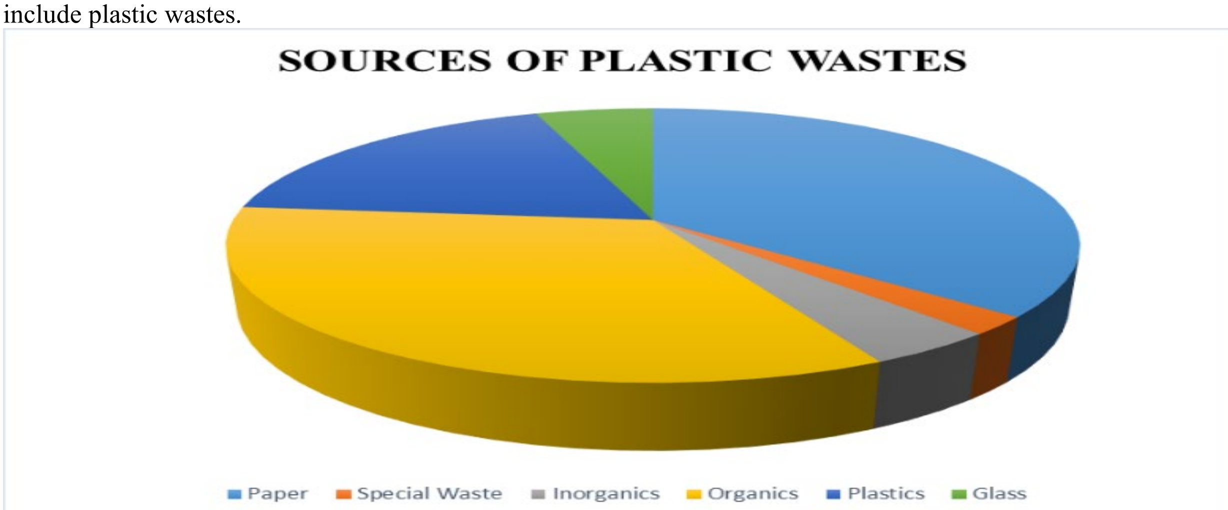

Figure 3 : Composition of municipal solid waste(Energy and Petroleum Regulatory Authority(EPRA), 2019; Kabeyi & Oludolapo, 2020)

From figure 3, it is noted that. Plastic wastes constitute a significant fraction of municipal solid waste for Nairobi city. Therefore, processing by pyrolysis as proposed in this study could help alleviate the problem.

MSW mainly contain low- density polyethylene, high-density polyethylene, polyethylene terephthalate, polypropylene (PP), poly- styrene (PS), and polyvinyl chloride. Generally, 50- 70% of the total plastic waste is packaging materials derived from polyethylene, polypropylene, polystyrene, and polyvinyl chloride. On average, polyethylene makes up the greatest fraction of all plastic wastes (69%), especially the plastic bags and polyethylene which have about 63% of the total packaging waste(Kunwar et al., 2016).

3.0. MATERIALS AND METHODS

The aim of the study was to determine quantity of waste plastics and hence the recycling potential based on the existing environment, quantities, and legal framework.

3.1 Methods and Procedures

Various techniques were used in the study to collect data and the impact the data will have on the design plant. Plastic waste was quantified in different parts of the countries through different agencies both in the public and private sectors.

i.) Data Collection

The data used in the design was mainly obtained through different methods. The first method was through the visit of various plastic manufacturing companies. Recycling companies also were vital areas for data collection since the current disposal of plastic wastes and recycling techniques were sought. One such company was Mr. Green Africa which is a plastic recycling company which provided vital information on the type of plastics recycled quantity collection and quantity recycled. The regulatory of manufacturers; The Kenya Association of Manufacturers also provided data on the number of plastics produced on the plastics produced in the country by various companies. The NEMA also provided data on the pollution status of plastics in the country.

ii.) SolidWorks 3-D Software

A computer software program, SolidWorks 2018 plant was used in the layout of the plant. The design incorporated the whole process from the waste ingestion to the washer and shredder up to the point high yield fuel was achieved. The software provides 3D modelling. The assembly of the plant was then arranged in order as illustrated in the design overview.

iii.) Analysis of Data

Once the appropriate data was collected was collected critical analysis was required to implement this on design of the plant. Analysis of the data collected from the various manufacturing and recycling company in terms of quantity would largely affect the size of the design plant. The data from NEMA, Nairobi City Council and Kenya Bureau of Standards (KEBS) also gave a hindsight about the quality of plastics being produced in the country and this was significant to ensure that the design plant met the required standards set by the regulatory body and the fuel produced met the environmental standards.

3.2 Cooling Tower Design

Height to diameter ratio $=\frac{Z_t}{d_b}$, Z_t = height to diameter ratio, Base diameter of the tower (d_b) = $\sqrt{\frac{4 \times A_b}{\pi}}$

where A_b = base area of the cooling tower, Base area of the cooling tower (A_b) = $\frac{D_t \times C_t^{1.5}}{19.5 \times Z_t^{0.5}}$,

Duty coefficient (D_t) = $\frac{19.5 \times A_b \times Z_t^{0.5}}{C_t^{1.5}}$, where C_t = performance coefficient (5.2 or lower)

Cooling capacity (Q) = $\dot{m} \times C_{pwater} \times \Delta T$ where C_{pwater} = 4.182KJ/kg. K, ΔT = change in temperature of water at the inlet of the tower to that of the outlet.

Cooling tower efficiency = $\frac{(T_i - T_o)}{(T_i - T_{wb})} \times 100$, where T_i = inlet temperature of water to the tower, T_o = outlet temperature of water from the tower, T_{wb} = wet bulb temperature.

Draft losses = 0.002% × mass flow rate of water.

Evaporation losses (E) $=\frac{C \times (T_i - T_o) \times C_p}{h_v}$

Where: - C = circulating water in m^3/hrs, h_v = latent heat of vaporization of water (2260Kj/kg), $(T_i - T_0)$ = water temperature difference from the top to bottom of the cooling tower. C_p = specific heat capacity of water (4.182Kj/kg. K)

3.3 Dry Scrubber and Flue Gas Chimney Design

The aim of the dry scrubber and flue gas chimney is to expel the harmful gases that result from the pyrolysis process in the reactor. The dry scrubber will contain calcium hydroxide which will be able to react with the acid gases. The gases produced from this process are mainly Sulphur (IV) oxide, carbon (IV) oxide and nitrogen (IV) oxide. These gases are harmful to the environment and living organisms.

The dry scrubber is lined internally with calcium hydroxide. This compound can react with the toxic gases from the pyrolysis process and ensure that the gases released to the atmosphere conform to the International Standards and national standards set by NEMA. Despite these efforts put in place a small amount of carbon (IV) oxide still escapes to the environment, but the rates will greatly be reduced. The calculations involved in the design of the chimney involves the pressure difference and the flue gas flow rate.

$$\Delta P = Cah\left(\frac{1}{T_o} - \frac{1}{T_i}\right)$$

where: - ΔP =available pressure difference, C =0.0342, a = atmospheric pressure in Pascal, h = height of the flue gas stack in meters, T_o= absolute outside air temperature, T_i= absolute average temperature of the flue gases inside the chimney.

4.0 DESIGN ANALYSIS

The main aim of this chapter was to analyze data collected from research and questionnaires carried out. Plastic production uses and flows over the years were studied. The main parts of the pyrolysis plant were also analyzed, and parameters were obtained from calculations carried out. The final plant layout was simulated using SolidWorks software. A cost benefit analysis was carried out to check whether the project was viable or not and a discussion at the end of the chapter was written down to see if the objectives were met.

4.1 Plastics Production in Kenya

This section will highlight the plastic overflow in the country. The data was collected in relevant government bodies associated with the plastic production and disposal in the country. NEMA put the production of plastics in March 2018, at 260,000 tons per year. According to KNBS and KRA the volume of plastics reduced by 3.8% due to a 21.8% decrease in the production of plastics carrier bags in accordance with the countrywide ban in August 2017. Data obtained from NEMA, through an economic survey also gave the input and export quantities of Kenya from 2013 to 2017. Table 2 below shows the plastic imports and exports from the Kenyan market between the year 2013 and 2017(Al-Salem et al., 2019).

Table 2: plastics production in Kenya (Kabeyi & Oludolapo, 2020)

Type	**Quantity(tons/year)**				
Exports	**2013**	**2014**	**2015**	**2016**	**2017**
Plates, sheets, strips	7,927	8,479	7,247	5,309	5,194
Articles of plastics	48,370	58,488	52,629	47,382	43,307
Total	**56,297**	**66,967**	**59,876**	**52,691**	**48,501**
Imports	**2013**	**2014**	**2015**	**2016**	**2017**
Plastics in primary/non primary form	377,340	400,188	455,432	469,426	453,784
Articles of plastics	37,770	49,786	46,138	50,649	42,346
Total	**415,110**	**449,974**	**501,570**	**520,075**	**496,132**

From table 2 above, it is noted that the net value of plastic products in Kenya has grown from 415,110 to 496, 132 tons in 2017. However, the quantity dropped between 2016 and 2017 when the government imposed a ban on plastic bags. This shows that the market has growth potential to supply a steady stream of plastics for recycling. The ban on plastic carrier bags significantly reduced the plastic quantities. The import rates are still significantly higher as compared to the imports, but government agencies continue to put tight rules to reduce plastics in the environment and reduce waste pollution. The continued drop in plastics export has been due to development of similar industries and products in Uganda and Tanzania who were the leading importers of Kenyan plastic materials(Ministry of Environment and Forestry, 2020).

4.2 Determination of Plant Capacity

15 tones and 2 reactors

$(15 \times 2) = 30$ tones $= 30$ tons $\times 365 = 10950$ tons/year

The number of plastics that can be recycled is 22,800 tons/year.

The % of plastics $= \frac{10950}{22800} \times 100 = 48.026\%$

The % of plastics to be reduced is $= \frac{10950}{202000} \times 100 = 5.421\%$

Various products can be produced using catalytic polymerization for plastic wastes. This is summarized in table 3 below.

Table 3: Catalytic polymerization (Author's summary)

ct	
l oil	% - 90wt%
	- 10wt%
	- 10wt%

The table 3 above below shows the weight percentage output of mixed plastics that result from catalytic reaction of pyrolysis. This data will be used to determine the fractions of either oil, gas or char that will be produced from the daily input of the plastic waste.

The total daily input = 30 tons

Lower input = $\frac{5}{100} \times 30$ = 1.5 tons and Upper limit = $\frac{10}{100} \times 30$ = 3 tons

The amount of gas that can be produced per day ranges from 1.5 tons to 3.5 tons.

Lower input = $\frac{81}{100} \times 30$ =24.3 tons, Upper limit = $\frac{90}{100} \times 30$ = 27 tons

The amount of liquid oil that can be produced per day will range from 24.3 tons to 27 tons.

Lower limit = $\frac{5}{100} \times 30$ = 1.5 tons, Upper limit = $\frac{50}{100} \times 30$ = 3 tons

The amount of char that can be produced per day will range from 1.5 tons to 3 tons.

4.5 Approximation of the Volume of Fuel Output

From the mass and energy balance for the catalytic pyrolysis. The volume of fuel was estimated as follows.

The value of catalytic oil produced = 25.65 tons per day (25650kg)

The density of standard pyrolysis oil = 860kg/m^3

Density (kg/m^3) = $\frac{\text{Mass}}{\text{Volume}}$; Volume = $\frac{\text{Mass}}{\text{Density}}$

Volume of oil produced per day = $\frac{25650}{860}$ = 29.826m^3

The expected volume of liquid of oil expected per day is 29,830 liters of oil per day. The deficits can be attributed to the amount of char produced from the pyrolysis process.

From the analysis above the percentage of oil produced per day is:

= $\frac{29830}{30000} \times 100$ = 99.433%

The volume of oil produced per batch in each reactor will be 14915 liters each.

4.6 Cooling Tower Specifications

Height to diameter ratio $= \frac{Z_t}{d_b} = \frac{70}{28} = 1.4$

Base area of the cooling tower

$A_b = \frac{C_t^{1.5} \times D_t}{19.5 \times Z_t^{0.5}}$ but from $d_b = \sqrt{\frac{4 \times A_b}{\pi}}$

A_b can also be expressed as $A_b = \frac{d_b^2 \times \pi}{4} = \frac{28^2 \times \pi}{4}$ A_b = 615.752m^2

Duty coefficient $D_t = \frac{19.5 \times A_b \times Z_t^{0.5}}{C_t^{1.5}} = \frac{19.5 \times 615.752 \times 40^{0.5}}{5.2^{1.5}}$ = 6404.208

Enthalpy change of passing temperature.

Range (ΔT) = $T_{in} - T_{out}$ = 323K – 301K = 22K

Approach (ΔT^*) = $T_{out} - T_{wb}$ = 301K− 297K = 4K

Mean temperature of the water = 0.5× ($T_{in} + T_{out}$) = 0.5× (363K+301K) = 332K

Using a humidity enthalpy chart and steam tables, we can calculate the values at the approach temperature and the dry bulb temperature.

Enthalpy change (Δh) = (101−16.5) kJ/kg = 84.5kj/kg

Cooling capacity

Q = hAΔT = 108.9 × 1963.495 × 62 = 13.257 MW

Water mass flow rate

$\dot{m}_w = \frac{Q}{C_{Pwater} \times \Delta T} = \frac{13257.125}{4.182 \times 62}$ = 51.1297 kg/s

Cooling tower efficiency

efficiency $= \frac{(T_i - T_0)}{(T_i - T_{wb})} \times 100 = \frac{(50-28)}{(50-24)} \times 100 = 84.615\%$

Make up water.

Evaporation losses

$E = \frac{C \times (T_i - T_o) \times C_p}{h_v} = \frac{(184.07) \times (62) \times (4.182)}{2260} = 21.1117KW$

from the cooling capacity of the plant, we can get the percentage evaporation losses $\frac{\text{Evaporation losses}}{\text{Cooling capacity}} \times 100$.

$= \frac{21.117}{10286.75} \times 100 = 0.2053\%$

Make up water calculations, from steam tables.

The relative humidity of Nairobi is 54%

At 24^0C - $P_s1 = 0.02982$ $h_{g1} = 2544.8Kj/kg$

At 30^0C - $P_s2 = 0.04242$ $h_{g2} = 2555.7Kj/kg$

$\Phi_1 = \frac{P_{v1}}{P_{s1}}$; $P_{v1} = P_{s1} \times \Phi_1$ $\Phi_2 = \frac{P_{v2}}{P_{s2}}$; $P_{v2} = P_{s2} \times \Phi_2$

$= 0.54 \times 0.02982$ $= 1 \times 0.04242$

$P_{v1} = 0.0161$ bar $P_{v2} = 0.04242$ bar

$\omega_1 = 0.622 \frac{P_{v1}}{P - P_{v1}}$; $0.622 \frac{0.0161}{1-0.0161} = 0.01018$

$\omega_2 = 0.622 \frac{p_{v2}}{P - P_{v2}}$; $0.622 \frac{0.04242}{1-0.04242} = 0.02755$

Water loss by evaporation $= \omega_2 - \omega_1 = 0.02755 - 0.01018 = 0.001737 \frac{kg_v}{kg_a}$

Energy Balance for make-up water

$C_p(T_2 - T_1) + \omega_2 h_{v2} + m_w(h_{w4} - h_{w3}) - \omega_1 h_{v1} - m_{w5} h_{w5}$

$1.005(323 - 301) + (0.02755 \times 2555.5) + m_w(117.3 - 209.3) - (0.0108 \times 2544.8) - 51.1297\ (0.01737 \times 62.9)$

$22.11 + 70.409 - 92m_w - 25.906 - 55.86 = 0$

$-92m_w = 55.86 + 25.906 - 70.409 - 22.11$

$m_w = 0.1168 \frac{kg_v}{kg_a}$

4.7 Flue gas chimney

$$Q = CA\sqrt{2gH\,\frac{T_i - T_o}{T_i}}$$

height of chimney = 20m, $T_i = 573K$, $T_o = 303K$, $C = 0.70$ hence

$Q = 0.70 \times (\pi \times 2.5)^2 \sqrt{2 \times 9.81 \times 20 \frac{(573-303)}{573}} = 13.744 \times 13.5978 = 186.888m^3/s.$

To calculate the velocity of the flue gases, we use the formulae Q = AV

where: - Q = volume of the flue gases in m^3/s., A= cross-sectional area of the chimney in m^2, V= velocity of the flue gases in m/s, $V = \frac{Q}{A}$, $= \frac{186.888}{\pi \times 2.5^2}$, $= 9.518m/s$

4.8 Energy Balance

The actual energy for conversion and cracking of plastic wastes to fuel is 1.328MJ/kg. Calculation of Energy balance per batch

Reactor capacity = 15 tons (15000kg)

The energy requirement $= \frac{1.328 \times 15000}{3600} = 5.533MW$

The production cycle time at the reactor during an 8-hour shift = $5.533 \times 8 = 44.2664MW$

Energy required for two reactors is $44.2664 \times 2 = 88.5328MW$

Energy consumption of the distiller = 0.05×8 hours = 0.4MW

Energy required by the cooling tower as calculated initially is 10.28675MW.

The total energy required per cycle will be given by:

Total energy = energy required for 2 reactors +energy required by cooling tower + energy consumption of the distiller =10.28675 + 88.5328 + 0.4 = 99.21955MW

Products such as char and gas will be an additional source of energy to the process. The formulation of these energies is:

The mass of char neglected during the process is 2.9% of the total waste.

$= 0.029 \times 30$ tons = 0.87 tons (870kgs), Converting the calorific value to KJ/kg

1 Cal/g = 4186.799993 J/kg hence (4500 × 4186.79993) =18840599.97 J/kg but 1 watt = 1 J/s hence

$=\frac{18840599.97}{3600}$ = 5233.49999 W/kg = 5.23 KW/kg

Energy from char can now be calculated = 5.23($\frac{KW}{kg}$) × 870 (kg) = 45501KW = 4.5501MW

energy produced per batch = $\frac{4.5501}{2}$ = 2.27505MW

The calorific values of pyrolysis gases = 20MJ/kg = $\frac{20 \times 10^6}{3600}$ = 5.556KW/kg

The percentage of gas produced from pyrolysis is 22%.

= 0.22 × 30 = 6.6 tons (6600kgs)

energy produced per batch = $\frac{5.556\left(\frac{KW}{kg}\right)\times 6600(kg)}{2}$ = 18.334MW

Total energy from gases and char = (18.334 + 2.27505) MW = 20.6905MW

Energy produced per cycle from the cycle = 20.6905 × 2 = 41.2917MW

The energy deficit is given by: = 99.21955- 41.2197 = 57.99985 MW

Energy from the oil.

The calorific value of pyrolysis oil = 46.1999MJ/kg

Converting to energy = $\frac{46.199 \times 10^6}{3600}$ = 12.833KW/kg

Amount of oil = 75.1% = $\frac{75.1}{100}$ ×100 = 20.277tons

Energy produced per batch.

$= \frac{12.833\left(\frac{KW}{kg}\right)\times 20277(kgs)}{2}$ = 130.107MW

The total energy produced from the process is 260.2147MW

To calculate the total mass flow rate of the fuel:

$Q = \dot{m}C_v$, $\dot{m} = \frac{260.2147\times 10^6 W}{46.199 \times 10^6 J/kg}$ = 5.632kg/s

4.9 Performance Test on the Pyrolysis Fuel

The pyrolysis fuel obtained from the process was found that it can be applied in engines. A test on a diesel engine was conducted to determine its efficiency. The diesel was tested on an engine with the following specifications.

Peugeot 306

Power = 70 HP (51Kw)
Angular speed = 4600rpm
4- cylinder
Brake drum radius = 129mm
Brake Torque = 120 Nm @ 2000rpm

P = $\frac{2\pi NT}{60}$= Brake power P = Tω where ω = $\frac{2\pi N}{60}$ = $\frac{2\pi\times 4600}{60}$ = 481.711rad/s

Q = ṁ C_v, ṁ= fuel consumption in kg/hrs, C_v = calorific value of the fuel hence

Q = $\frac{5.63247}{3600}$× 46.199×10^{6} = 72281.8KW

Brake power = Tω=481.711×120= 57805.32 KW and

Brake thermal efficiency = $\frac{\text{Brake power}}{\text{Fuel power}}$ = $\frac{Bp}{\dot{m}\times Cv}$ = $\frac{57805.32}{72281.8}$ η= 0.79972 η= 79.972%

The test above on the Peugeot diesel engine showed that the diesel oil obtained from pyrolysis was as efficient as the diesel produced from fossil fuel. The efficiency of 79.92% shows the pyrolysis fuel can easily be applied on diesel engines.

4.10 Cost Benefit Analysis

An analysis of the cost linked with the plant is tabulated as provided. It is based on the feed rate, hours in service and the number of batches. Revenue realized is based on capital expenditure and financing options, operating expenditure, net present value and total revenue and operating incomes is analyzed to obtain a quotation for the finances needed. The operating income will be calculated from the difference between the total product revenue and the grand total cost of the first year in operation.

=Ksh. 1,203,045,600- 950,148,000=Ksh. 252,897,000

NPV=$\sum_{t=1}^{T} \frac{C_t}{(1+r)^t}$- C_o

The value over the years will be calculated by deducing the total revenue cost over the years and subtracting the set-up cost of the plant to the number of years it would take the plant to start making profits. Table 4 below shows the projected net present value for the proposed pyrolysis plant.

Table 4: Net Present Value of the project

Period	NPV(Ksh.)
Year 1	-958,148,000
Year 2	-705,251,000
Year 3	-452,354,000
Year 4	-199,457,000
Year 5	53,400,000

Table 4 shows that the payback period for the project based on the projected design capacity and operational parameters is five years.

For the net present value

$$\sum_{t=1}^{T} \frac{C_t}{(1+r)^t} - C_o = \frac{252{,}897{,}000}{(1+0.1)^1} + \frac{252{,}897{,}000}{(1+0.1)^2} + \frac{252{,}897{,}000}{(1+0.1)^3} + \frac{252{,}897{,}000}{(1+0.1)^4} + \frac{252{,}897{,}000}{(1+0.1)^5}$$

= 229,906,363.6 + 209,005,785.1 + 190,005,259.2 + 172,732,053.8 + 157,029,139.8= Ksh. 958,678,598.5

The current net present profit would be calculated as the NPV and removing the total operating costs. The current net present profit would be calculated as the NPV and removing the total operating costs.

=Ksh. 958,678,598.5 – 950,148,000= Ksh. 8,530,598.5

4.11 Economic Analysis of the Pyrolysis Oil

From the few research done on the pyrolysis oil and cost incurred, the market price was set at Ksh. 80 per liter. The fossil fuel currently being imported retails at Ksh. 96.60 per liter. Kenya's monthly consumption currently stands at 210 million liters per month.

Using the market price, we can calculate the monthly budget Kenya incurs:

210,000,000 × 96.60 = Ksh.20.286 billion

The pyrolysis oil monthly budget will be:210,000,000 × 80.00 = Ksh.16.80 billion

The above analysis shows that the country, if many pyrolysis plants can start up, will save the country approximately 3.486 billion monthly. This translates to about 41.832 billion per annum. The Kenyan budget is approximately 3 trillion. If the country can save up on 41.832 billion, the percentage it will impact on the economy can be given by:

$= \frac{41.832}{3000} \times 100 = 1.3944\%$

A reduction of 1.3944% towards the economy will have a great impact whereby the funds can be implemented on other sectors like roads, health, education, and infrastructure.

5.0. CONCLUSIONS

There has been rapid growth of production of plastics in the world due to growing demand. They are mostly used as packaging of materials and containers Since they do not degrade, the best way to dispose them off is by recycling. Despite the ban on plastic bags, we still have a lot of plastic waste that should be handled and disposed. There are various ways of recycling of plastics, but pyrolysis promises to be an effective and cost-effective way of disposal. The pyrolysis plant has a capacity to produce 24,300 liters to 27,000 liters of oil from 30 tons of plastic waste. The plant has a yearly capacity of about 10950 tons. From the data of imports and exports of plastics it noted there has been a steady decline in exports across the years from 2014-2017. On the other hand, imports to the country have been increasing across the years due to the growing demand of plastics in the country even as exports have diminished over years. Blending the pyrolysis oil with alcohols has been proven to improve fuel properties in terms of acidity, corrosiveness, volatility, ignition temperature, heating value and energy density and this further reduces the environmental impact because of plastic oil pyrolysis. Alcohol content of up to 20% in diesel can be used in internal combustion engines (ICE) without any modifications. Methanol and ethanol due to their high latent heat of vaporization compared to diesel offer longer ignition delay period of combustion. Mixing of alcohol with pyrolytic oils helps improve undesirable qualities in terms of heating value, viscosity, and acidity. Solvent addition can prevent pyrolytic oil from aging effects.

Implementation of the project will provide a solution to the challenge of plastic pollution in the country which is a has no such facility. It also provides economic benefits as calculated from the cost benefit calculations done whereby the annual profits made after five years was seen to be Ksh. 8,530,598.5 therefore returning investment costs. This therefore indicates that the proposed project is viable project to undertake. Analysis based on market prices showed that about 210 million liters of cheaper fuel can be made annually.

6.0. RECOMMENDATIONS

6.2.1 Broad recommendations

i. The only amount of data collected was from few institutions due to time constriction, but we recommend there be more institutional visits to collect appropriate data for the design process.
ii. Proper waste collection systems need to be set up to make recycling process more efficient.
iii. Data on plastic wastes should be updated since most of the collected were from local authorities, reports and documents. Proper data would have helped in the proper design of the plant setup.
iv. Proper waste management systems should be established to set pace to effective plastic waste recycling.
v. Provide continuous awareness to the public on plastic waste effects on the environment, aquatic life, and human health to find ways of setting up better waste management systems.
vi. Make legislations that aims to make companies set up plants to undertake these types of projects.
vii. Provide incentives for investments so that they may undertake such type of projects.
viii. Call out investors to undertake these types of projects.

6.2.2 Recommendations for further research

i. For specifications on pyrolysis oil applications there was need on testing the application of the fuel after addition of additives which were meant to improve fuel properties.
ii. A theoretical approach to the design but we recommend a practical approach for analysis of the fuel so that realistic results may be obtained.
iii. There is need of further research on ways to improve fuel properties of the pyrolysis fuel due to time constriction this could not be achieved.
iv. To investigate on how to lower the amount of water produced during the pyrolysis process that may affect the fuel injectors.

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Author Biographies

Moses Jeremiah Barasa Kabeyi is currently pursuing his D.Eng. In Industrial Engineering in the Department of Industrial Engineering at Durban University of Technology. He earned his B.Eng. degree in Production Engineering and MSC in Mechanical and Production Engineering (Energy) from Moi University, in Kenya, MA in Project planning and Management from University of Nairobi, in Kenya and Diplomas in Project management, Business management and NGO management respectively from The Kenya Institute of Management. He has worked in various factories including sugar manufacturing at Nzoia Sugar Company Ltd, pulp and paper at Pan African Paper Mills EA Ltd, and power generation at the Kenya Electricity Generating Company (KenGen) in Kenya, in an industrial career of 16 years before moving into teaching. He has taught in various universities in Kenya including University of Nairobi, Technical University of Mombasa, and Egerton University and currently on study leave. His research interests are power generation, fuels and combustion, internal combustion engines and project management and sustainability. He is registered with the Engineers Board of Kenya (EBK) and Institution of Engineers of Kenya (IEK) and has published several journal papers.

Oludolapo Akanni Olanrewaju is currently a Senior Lecturer and Head of Department of Industrial Engineering, Durban University of Technology, South Africa. He earned his BSc in Electrical Electronics Engineering and MSc in Industrial Engineering from the University of Ibadan, Nigeria and his Doctorate in Industrial Engineering from the Tshwane University of Technology, South Africa. He has published journal and conference papers. His research interests are not limited to energy/greenhouse gas analysis/management, life cycle assessment, application of artificial intelligence techniques and 3D Modelling. He is an associate member of the Southern African Institute of Industrial Engineering (SAIIE) and NRF rated researcher in South Africa.