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Evaluation the effect of the temperature and the type of plastic waste feedstock on the thermal pyrolytic oil fuel.

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Abstract

Recently, the pyrolysis pops up as an effective and appropriate method to benefit from plastic waste and converting it into fuel, which has been addressed by many scientific studies, in this current practical study, six types of plastic waste (PP, PS, LDPE, PET, HDPE and plastic waste mixture PWM) were used to study the influence of the various temperatures (400, 450, 500, 550 and 600 ^{o}C) on the amount of oil was produced from a thermal pyrolysis using a semi batch reactor 2.3 liter capacity, the experiments showed that, When oil is the preferred product of the pyrolysis process, PS type produced the large amount of oil (82.5%) by mass analysis at optimum temperature 450 ^{o}C, on the other side PET produced the best amount of gas (85%) at 600 ^{o}C therefore PET was the most appropriate choice when the gas form is the preferred product, temperature had a great effect on the pyrolysis products, at low temperature, the char product was the dominant product from pyrolysis, the oil product clearly appear with the temperature gradually rising for almost types of plastic which does not last as the temperature continues to increase, at high temperature the gas percentage increases at the expense of the liquid percentage decreases

1 Introduction

In recent decades, the consumer demand for plastic products in a continuous increase coinciding with the continuous population growing, so the plastic has become the superior material and major key for many sectors and industries as the automotive industry, building and construction, the health sector, and various household purposes....etc, due to its lightweight, fixed chemical, formation facility, low cost and durability [1], at the global level, plastic production has reached 368 million metric ton at 2019 at rate by 2.51% over 2018 product, out of the trend the plastic production rates decreased in 2020 at 367 million metric ton reduced rate by 0.3% compared to 2019, due to the precautionary measures that were applied by the world to face the spread of the new Corona virus(Covid 19)[2].

On the opposite side, the continuous increasing in the consumption of plastic products has led to increase in the accumulation of solid plastic waste (SPW), with the difficulty of decomposing these wastes and the ineffectiveness of traditional mechanical methods for recycling these wastes, these were the main reasons for the increase in the spaces of these wastes in landfill, seas and oceans, which produced a major environmental threat danger on the human and animal life [3].

Landfill management face the problem of energy recovery from SPW by mechanical technology as recycling that recovery about 10% from SPW, this is due to the difficulty of separating plastic waste, especially the new composite materials, in addition to the high costs for the collection and separation processes, Therefore, scientific studies is necessary to search for new techniques to recover wasted energies from plastic waste [4].

Thermo chemical technology recycling as pyrolysis has attracted more attention from scientific research as a promising and alternative method of traditional mechanical recycling to recovery the energies from plastic waste, the pyrolysis is thermally pyrolysis of SPW requires intense heat and pressure with absence of oxygen and shorter duration time to convert chain polymer molecules in to smaller and less complex molecules in liquid, gas and char forms, many studies showed that the pyrolysis able to produce a high yield of liquid oil product has similar the diesel fuel properties up to 80 wt% at a temperature around 500^{o}C [5], this percentage may increase up to 90 wt% [6].

Many experimental studies dealt with various factors that affect the type, quantity and quality of the products of the thermal pyrolysis process, such as the type of feedstock, the type and design of the reactor, temperature, heat rate, reaction time and condensation system, but there was almost agreement that the temperature is the most important parameter in the type and quantity of the product [1–6, 9, 12, 19& 20].

Most researchers tended to obtain the largest possible amount of the pyrolysis process in the liquid oil form as alternative bio-fuel for diesel fuel in internal combustion engines, however, these studies showed a large variation in the amount of oil product from pyrolysis process despite the great similarity in the operating conditions of the experiment.

2 Material And Apparatus

2.1 Feedstock preparation

The materials of feedstock were collected from various plastic waste products as water containers, grocery bags, one-use plates, drinking water bottles, and food containers cups that represented HDPE, LDPE, PS, PET, and PP plastic types respectively, all these previous types of plastic products are the main sources of plastic waste in Egypt, the six type is PWM form consists of equal weight ratios of the previous five types of plastic waste, at the beginning, feedstock was washed well then crushed to small parts (about to 3 cm^2) to get a good and homogeneous mixture to improve chemical reaction in the pyrolysis process.

The previous six feedstock were tested in a little scale pyrolysis reactor was selected to convert the plastic waste into liquid oil, gas and char products (Fig. 1). The reactor cylinder was made of cast iron 6 mm thickness and wrapped with a loop of an electric heater 2 meters length and 3 kW capacity, the height of the reactor was 290 mm with 100 mm diameter and a capacity of 2.3 liter (Table 1). Connected with a tube 20 mm. diameter that pass inside the condenser tube with a length of 600 mm and 60 mm diameter, which equipped with two entrances to pass the cooling water, the bottom is the entry and the top representing the exit. The vapors of plastic waste produced in the heating chamber at high temperature were condensed into liquid oil in the condenser tube. The water circulating passes the condenser tube by 1.7 liter/min flow rate the condensed liquid oil was collected in the oil collector tank at the bottom of the system, while the uncondensed products (gases) were exhausted outside (Fig. 1).

2.2 Experimental setup and precautions

Through all of the experiments, 50 g of plastic waste feedstock for each plastic waste type was measured by digital weight 0.1 accuracy, each type of PWF was used in the reactor; the pyrolysis reactor was heated from room temperature to a required temperature using an electrical control unit with a heating rate of 23.6 ^{o}C/min, the time of the beginning of the first drop of oil, the time of the end of the last drop and the color of gas product were one of the most important considerations that was recorded during each experiment, at the experiment end The mass of oil in collector tank and the rest char inside the reactor is calculated by the digital weight and by applying the law of mass equilibrium, the mass of the gas is calculated.

Table 1. Reactor components parameters

component	features
Height reactor tank	290 mm
Diameter tank	100 mm
thickness tank	6 mm
capacity	2.3 liter
thermo couple	type K
heater	2 meters & 3 kW
condenser diameter	60 mm
condenser length	600 mm

3 Results And Discussion

Figures (2–7) showed the effect of the temperatures (400 ^{o}C to 600 ^{o}C) Increasing by 50 ^{o}C on the six types of plastic waste, the details as following

3.1 LDPE type

Pyrolysis of LDPE products against the various temperatures are depicted in Fig. 2. LDPE is characterized by being better ductility, easier to be molded, less crystalline structure and better water resistant than HDPE so it is widely used in the plastic bags which are used in this experiment.

Fig.2. showed that the amount of the oil produced increases with increasing temperature during temperature range (400 ^{o}C to 550 ^{o}C), the largest amount of oil is obtained 69% at 550 ^{o}C, with 22% gas and 10% char. This amount was very close to the authors in [7] they found 74.7 % oil product by using batch reactor at 450 ^{o}C, in another trend in the study in [8] it was recorded the highest amount of oil at 93.1% at optimum temperature 550 ^{o}C, this high percentage may be that the researchers used the LDPE feedstock in the a powder form at maximum size 500 μm,

With the increase in temperature in the present study to 600 ^{o}C the oil decreased to 38% and the gas percentage increased to 53%, this increase in gas is a result of secondary reaction of oil to convert oil to gas this agreement with the authors in [9].

3.2 HDPE type

HDPE has high strength properties because it is a long polymer chain with high crystalline and low branching, Therefore, HDPE is widely used in detergent and dairy bottles, children's toys, water and oil containers, which is used in this laboratory study.

Figure 3. showed that the effect of temperature on the products of the HDPE pyrolysis process, during the experiments run at temperatures 400 ^{o}C and 450 ^{o}C, it was observed that part of the HDPE vapors condensed on the wall of the oil collector in the form of yellowish brown wax 27% at 450 ^{o}C instead of liquid oil, this phenomenon is in agreement with the researchers [10] their study showed that thermal PE pyrolysis produced maximum oil 25% at 450 ^{o}C in wax form instead of liquid with 62% gases and 13% char by using a small batch reactor 30L capacity and 10 ^{o}C /min.

With an increase in the temperature to 500 ^{o}C and above, liquid oil droplets were observed and after a period of time it turned into wax, the maximum oil/wax is obtained 63%, 29% gases and 8% char at optimum temperature 550 ^{o}C, the researchers S. Kumar and R. K. Singh [11] they recorded close to these results, their study showed that the maximum oil/wax were 7.86% and 71.22% at 550 ^{o}C respectively by using a batch reactor, 20 ^{o}C /min heat rate.

By increasing the temperature to 600 ^{o}C, the oil produced decreased to 41%, while the amount of gas increased to 52%, 7% for char.

3.3 PS type.

PS is styrene monomers, the chemical structure of PS is a long string from hydro-carbon with phenyl group connected to another carbon atom, strength, lightness, credible durability, heat resilience and colorless these are the essential characteristics of PS that make it desired to be used in many various of industrial applications and sectors such as in one used food plates, that are used in this study.

Fig.4. indicated the effect of temperature on the thermal PS pyrolysis, at 400 ^{o}C PS type produced a large amount of oil dark black 55%, 35% gases and 10% char, but the maximum of oil was achieved at optimum temperature at 450 ^{o}C, oil produced at 82.5%, 15% gases and 2.5% char, with increasing the temperature caused a decrease in the amount of oil in return, an increase in gas percentage, at 600 ^{o}C oil decreased to 68%, 30% gas and 2% char, this was explained by the fact that a part of the amount of oil evaporated into gas due to the increase temperature, this trend completely agreed with the study [10] the authors found the maximum oil produced from thermal PS pyrolysis was 80.8% at optimum temperature 450 ^{o}C

Increasing gas product with decreasing oil yield at high temperature was explained by the authors in [12] they showed that at the higher temperature on optimum temperature some a secondary reaction was occurred to start the polyaromatic formation reactions that decreased styrene yield and the liquid oil product.

On the other trend the authors in study [9] they showed that the thermal pyrolysis of PS type produced a very high score liquid oil product was about 97.0% wt and minimum gas yield 2.5% wt. at optimum temperature 425 ^{o}C, these high results because of the controlled condition of this study as a pressurized batch reactor 0.3 L capacity, 10 ^{o}C/min heat rate, 1.26 MPa operating pressure and one hour time duration.

3.4 PET type

chemical stability Strength, hygienic use, and corrosion resistance are the essential properties that distinguish PET from other types of plastic and become it the ideal choice for food containers, soft water and juices bottles [13]

Fig.5. showed the effect of temperature on the PET pyrolysis products, it is clear that PET is very poor in oil production. where the highest amount of oil is recorded 3% at a temperature of 400 ^{o}C and with the increase in temperature, the amount of oil decreased until it almost disappeared 1% at 600 ^{o}C, on the contrary, for gas product, the increase in temperature increased the amount of gas to a very large yield 85 % at 600 ^{o}C. This results is in agreement with the authors in [14], their study showed that the oil and gas yield is recorded 21 g. (1.4% wt.) and 1029 g. (68.6% wt.) respectively from 1500 g. PET feedstock by using the waste water bottles in a fixed bed reactor at 450 ^{o}C and 2500 Watt electrical heater, on the same trend, the study in [15 the researchers recorded zero of the oil produced during each temperature range (300 ^{o}C to 700 ^{o}C). The small amount of oil resulting from the PET pyrolysis has been explained by researchers in [5] they showed that the waste PET has the lowest volatile matter compared the others plastic waste types.

3.5 PP type

PP is widely used in industrial products that are frequently used in our daily life, such as textiles, auto parts, home furniture, packaging supplies and food containers, due to PP has a high heat and chemical resistance, rigidity and higher hardness compared with HDPE type.

Figure 6. shows the effect of temperature on the product of the PP pyrolysis process at 400 ^{o}C recorded the amount of oil 5%, gas 45% and char 50% and with increasing temperature the amount of oil increased until it reached its highest levels at the optimum temperature 500 ^{o}C and reached at 47.5%, gas 42.5% and char 10% and by increasing on the optimum temperature to 600 ^{o}C the amount of oil decreased to 20%,while the amount of gas increased to 75% and char 5%.

The researchers in [10] largely agreed with these results, their studies showed that the largest amount of oil produced from PP pyrolysis at 42% wt but at another optimum temperature 450 ^{o}C, with 54.5% gas, and 3.5% char. On the same trend, A. Demirbas in [16] his study indicated that the maximum oil product from PP pyrolysis is obtained at 48.8% wt and 49.6% wt for gases, but at another optimum temperature 740 ^{o}C by using a batch reactor, and 10 K/min heat rate .

On the other trend, the authors in [17] their study was recorded a higher oil product from pp thermal pyrolysis 64.9% with 24.7% for gases at optimum temperature 380 ^{o}C by using a glass batch reactor, 3 ^{o}C /min and 300 mm. l. capacity.

3.6 Mixture plastic waste type

The thermal pyrolysis of PWM has attracted the interest of many researchers to recover energy from plastic waste, because the p.w.m. pyrolysis is the ideal technique for the waste, which is difficult to sort into specific types, and as a result, the thermal pyrolysis of the mixture requires less labor and therefore is better economically.

The present experimental study of the p.w.m. pyrolysis indicated that, at low temperature 400 ^{o}C is recorded minimum oil produced at 5%, with 45%and 50%wt for gases and char yield respectively, with increasing the temperature, the oil product in creased at maximum amount 40% at optimum temperature 500 ^{o}C, with 45% and 15% for gases and char yield respectively, at high temperature 600 ^{o}C, oil yield decreased to 28.75% and gases is recorded maximum amount 60% with a small char is obtained at 11.25%, this results are showed in Fig. 7.

Close to these results, the authors in [18] their study is showed that the maximum amount of oil yield is obtained at 48.4% at optimum temperature 650 ^{o}C, with 36.9% and 15.7% for gases and char respectively, these results are recorded by using a fluidized quartz-bed thermal pyrolysis, 1–3 kg/h capacity, and the mixture consisted of 46% LDPE, 30% HDPE and 24% PP.

On the same trend, the study in [10] the authors recorded the largest amount of oil at 40% at optimum temperature 450 ^{o}C, with 42%, 18% for gases and char respectively, when the mixture consisted of 40%, 20%,20% and 20% for PS, PE, PP and PET.

On the other side, the researchers in [19] their study is obtained the maximum oil produced 72% wt at optimum temperature 460 ^{o}C, with 26.9% and 1.1% for gases and char respectively, these results are recorded by using a semi batch reactor 3.5 L capacity, thermal pyrolysis, 20 /min heat rate and the mixture consisted of 40%, 35%, 18%, 4% and 3% for PE, PP, PS, PET and PVC.

4. Pyrolytic Oil And Its Applications.

Fig.8. included the effect of temperature on the oil produced from each type of plastic, it showed that PS type is recorded the highest amount of oil during all temperatures compared the others types, this

agreement with [9, 10&12], PS type is obtained the maximum oil 82.5% at 450 ^{o}C, on the opposite side, PET is a type that produced very little oil, especially at high temperatures compared the others types, where the oil produced from PET pyrolysis is about to disappear, so PET is not preferred if the desire to obtain oil from pyrolysis process.

The oil resulting from the pyrolysis process has many properties that make it an alternative source of energy, as it is very similar when compared to transportation fuel. Many research studies have dealt with evaluating the performance of the efficiency and emissions of the pyrolytic oil when blended with conventional diesel fuel in internal combustion engines [20].

5 Conclusion

The current study presented the importance of the thermal pyrolysis process to recover energy from SPW, and the following conclusion was drawn from the results of the current study.

1. Thermal pyrolysis process is the best way to recycle wasted energy from SPW, which was destined for landfills.
2. Temperature is one of the most important factors affecting the type (oil, gases, wax and char) and quantity of the product of the pyrolysis process at most types, char is obtained at low temperature, but gases is obtained at high temperature and liquid oil is obtained between two limits.
3. PS pyrolysis type is produced the largest pyrolytic oil yield 82.5% at optimum temperature 450 ^{o}C, while PET pyrolysis type is produced a very little of oil.
4. PET pyrolysis type is produced the maximum pyrolytic gases 85% at 600 ^{o}C, so it is preferred when the resulting gas is desired.
5. The pyrolytic oil produced from the pyrolysis process is very similar to diesel fuel, so blends of oil and diesel fuel are tested in internal combustion engines.

Nomenclature List

HDPE	High Density Polyethylene	PS	Polystyrene
LDPE	low Density Polyethylene	PWM	plastic waste mixture
PET	Polyethylene Terephthalate	SPW	solid plastic waste
PP	Polypropylene		

Declarations

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Author's contributions

- Abd Elhafiz A. Ali conducted set up apparatus and waste plastic materials, experiments, discussed and analyzed the results, and wrote the manuscript.
- Dr Seddik contributed the design of pyrolysis plant, followed up on experiments and gives feedback, revised and proved the manuscript.
- Dr Salah revised the all parts of manuscript to be submitted.

Conflict of interest

all authors announce no competing interests.

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Figures

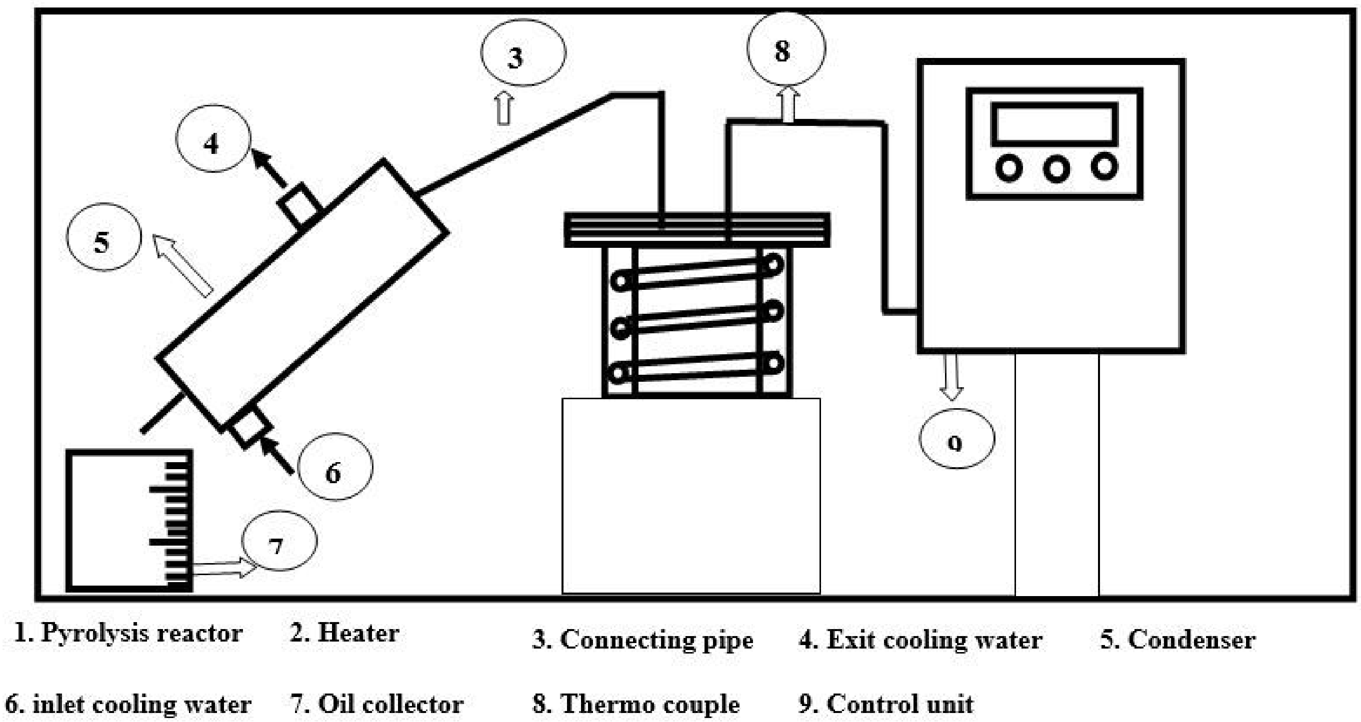

Figure 1

The schematic of the plastic waste pyrolysis unit.

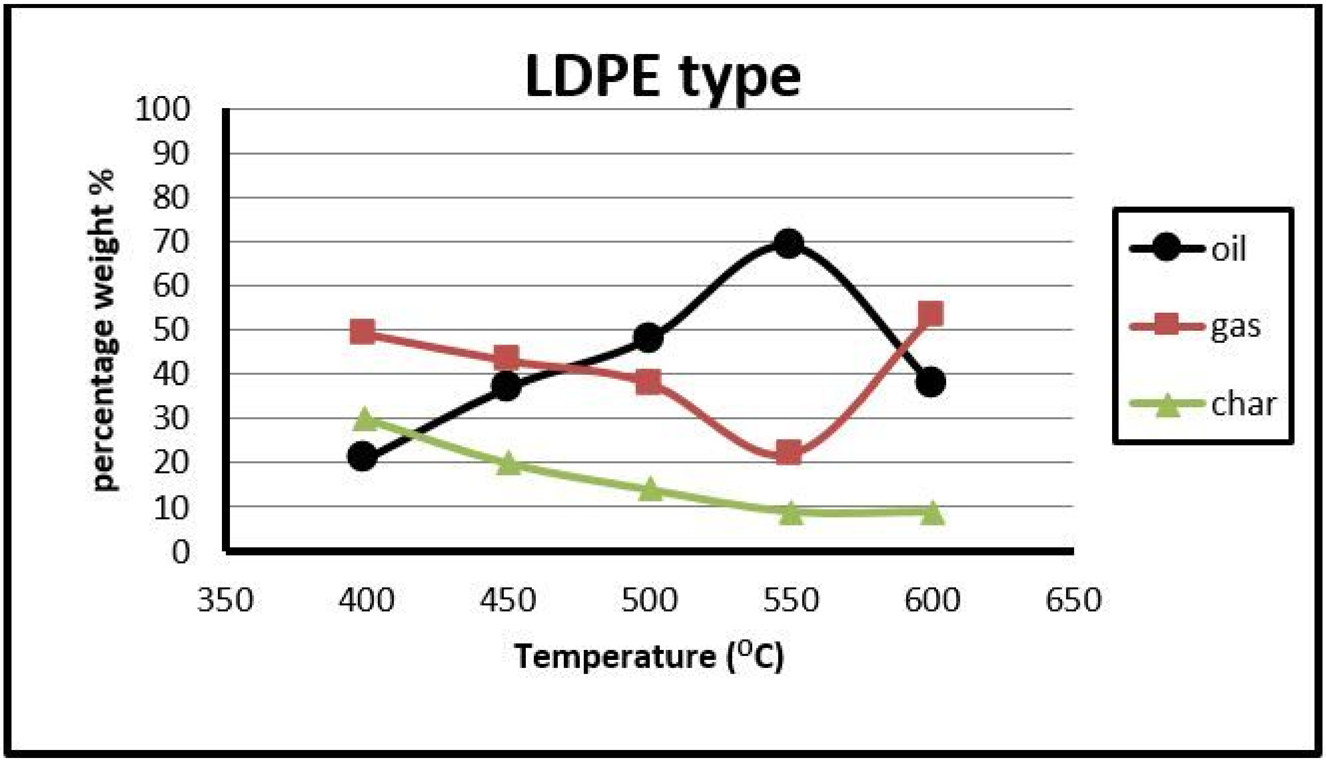

Figure 2

temperature versus LDPE pyrolysis product yield.

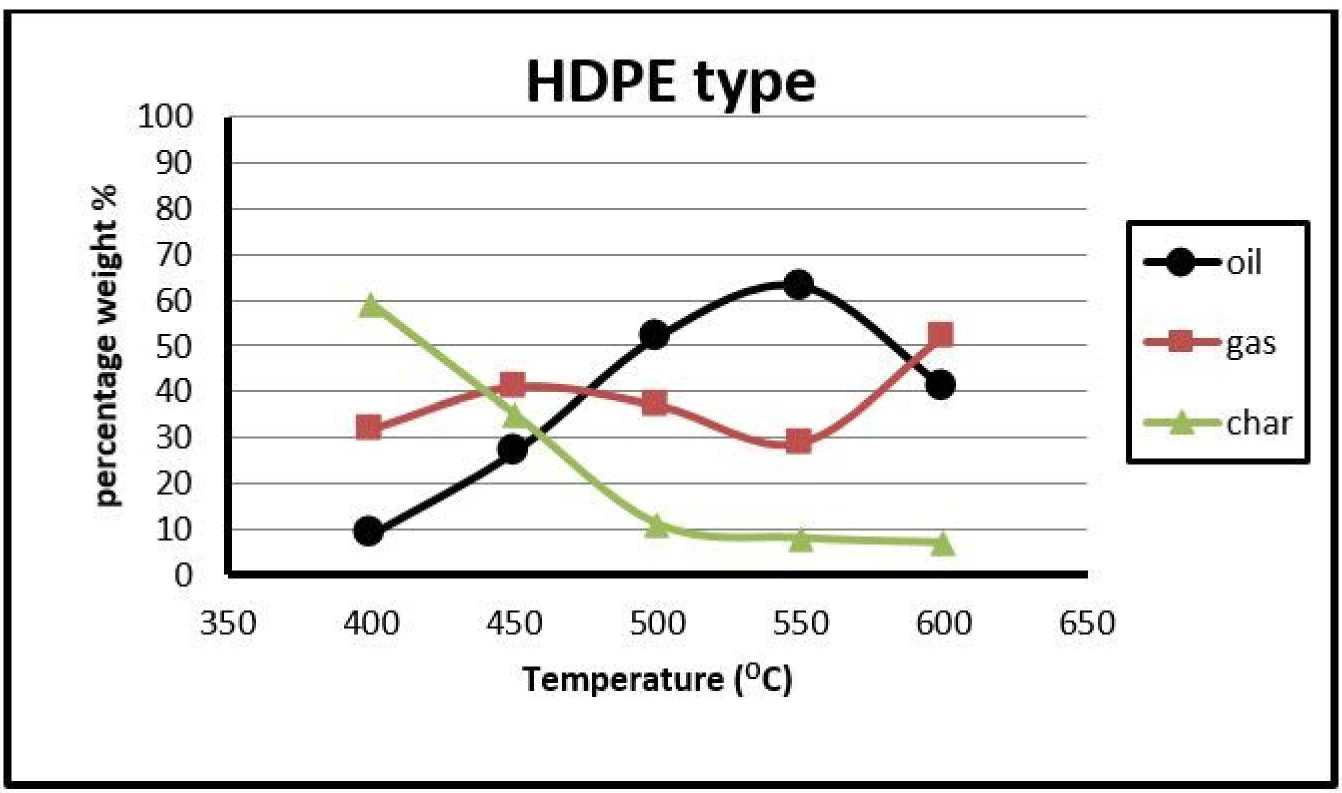

Figure 3

temperature versus HDPE pyrolysis product yield.

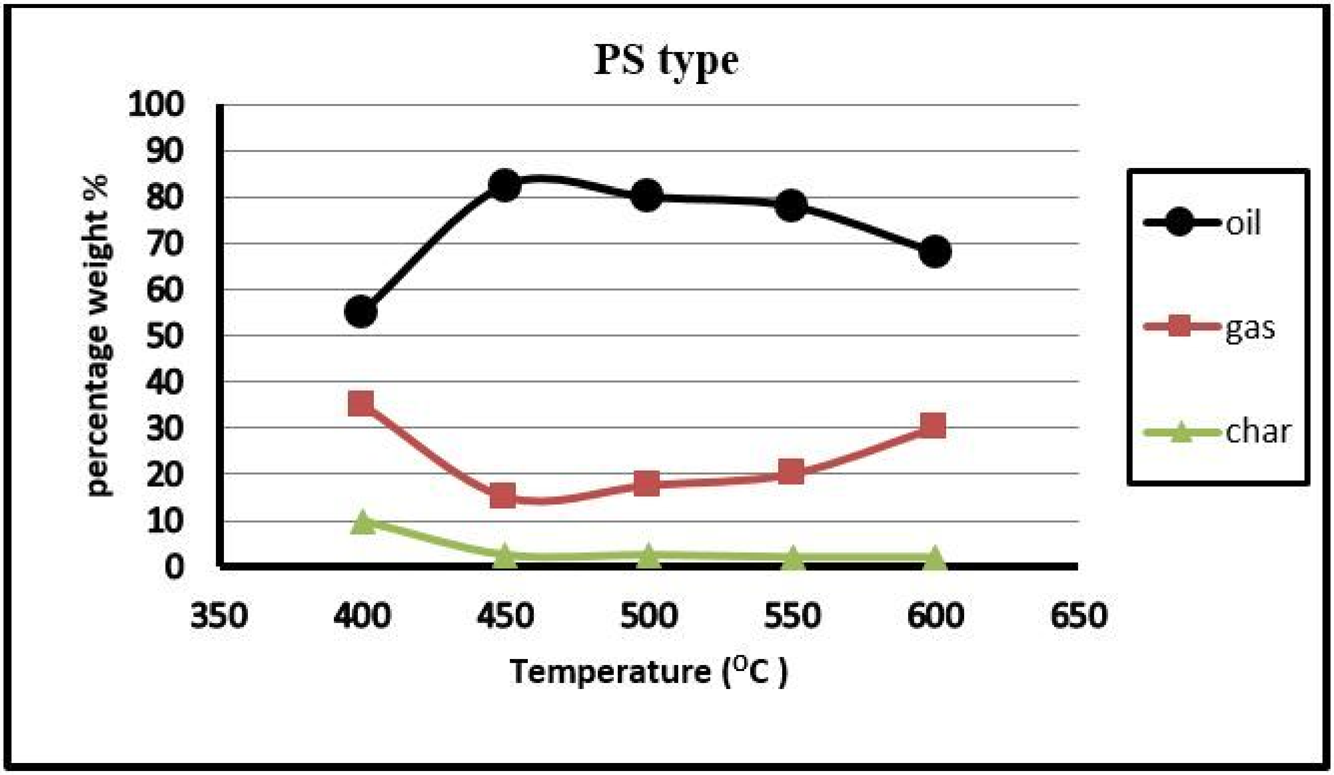

Figure 4

temperature versus PS pyrolysis product yield.

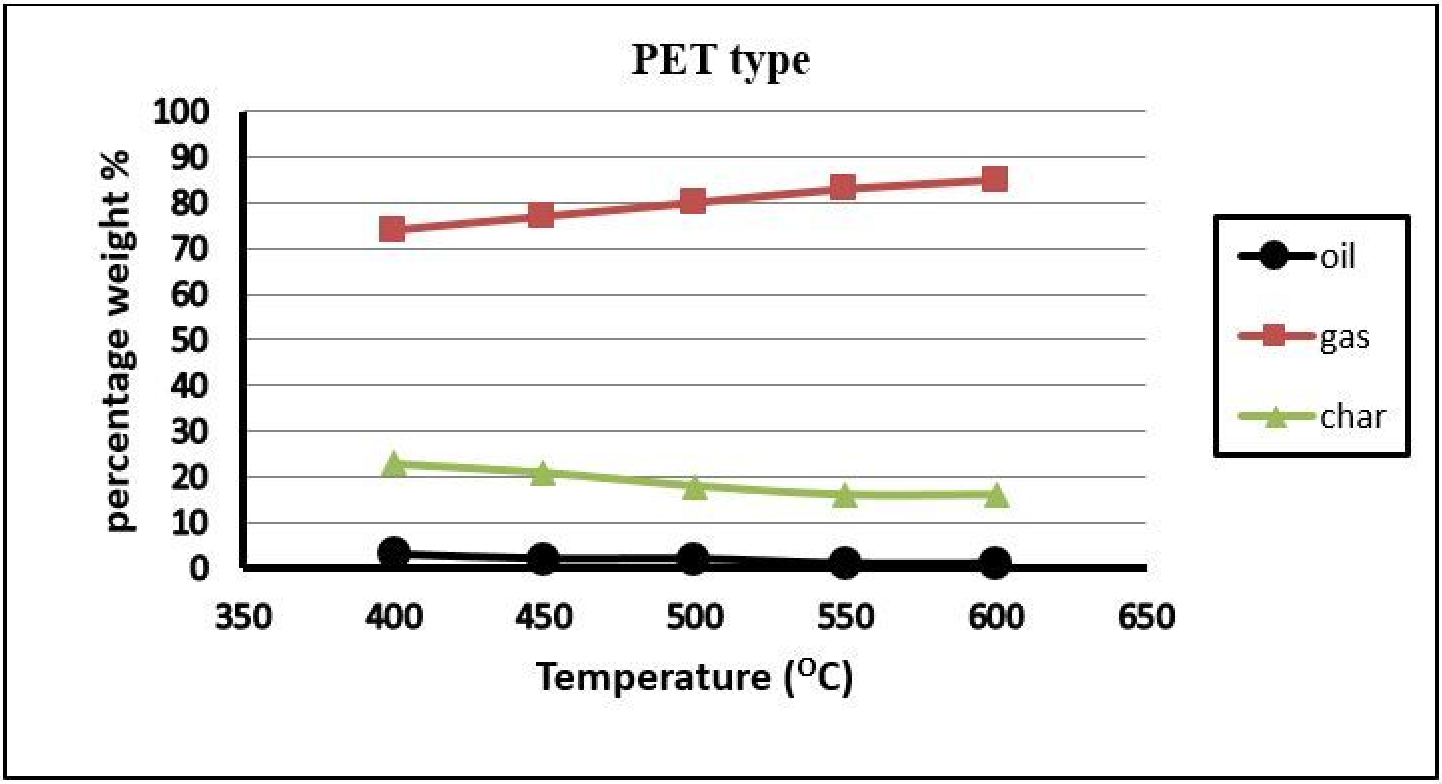

Figure 5

temperature versus PET pyrolysis product yield.

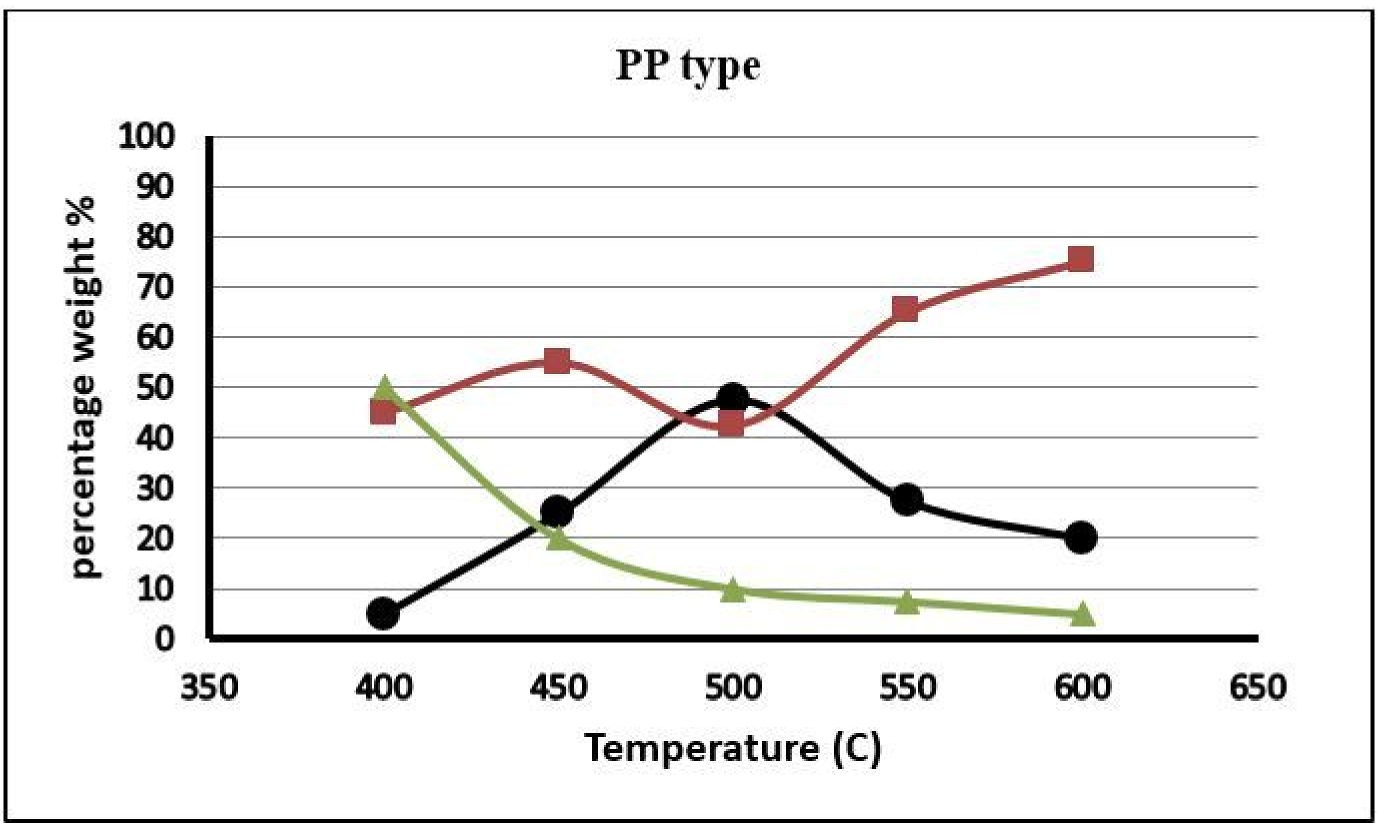

Figure 6

temperature versus PP pyrolysis product yield.

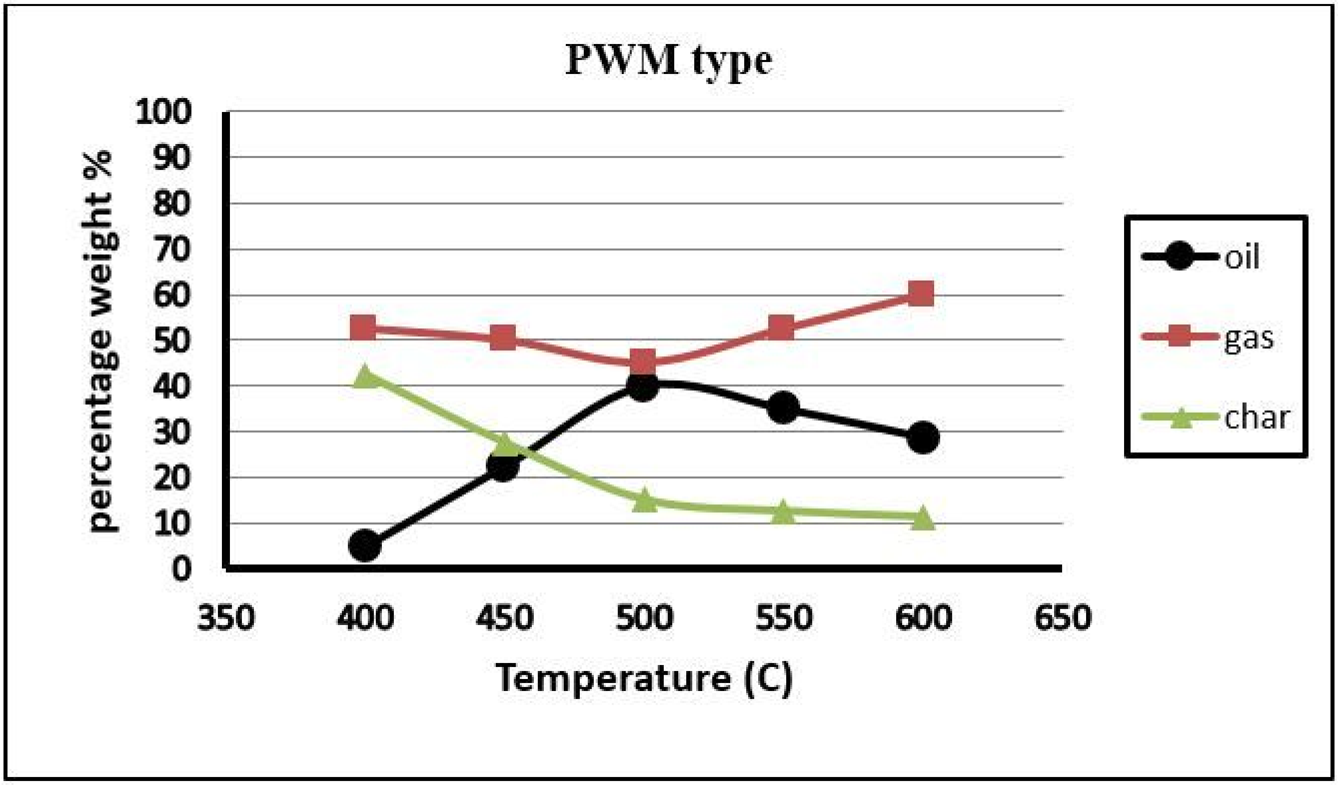

Figure 7

temperature versus PWM pyrolysis product yield.

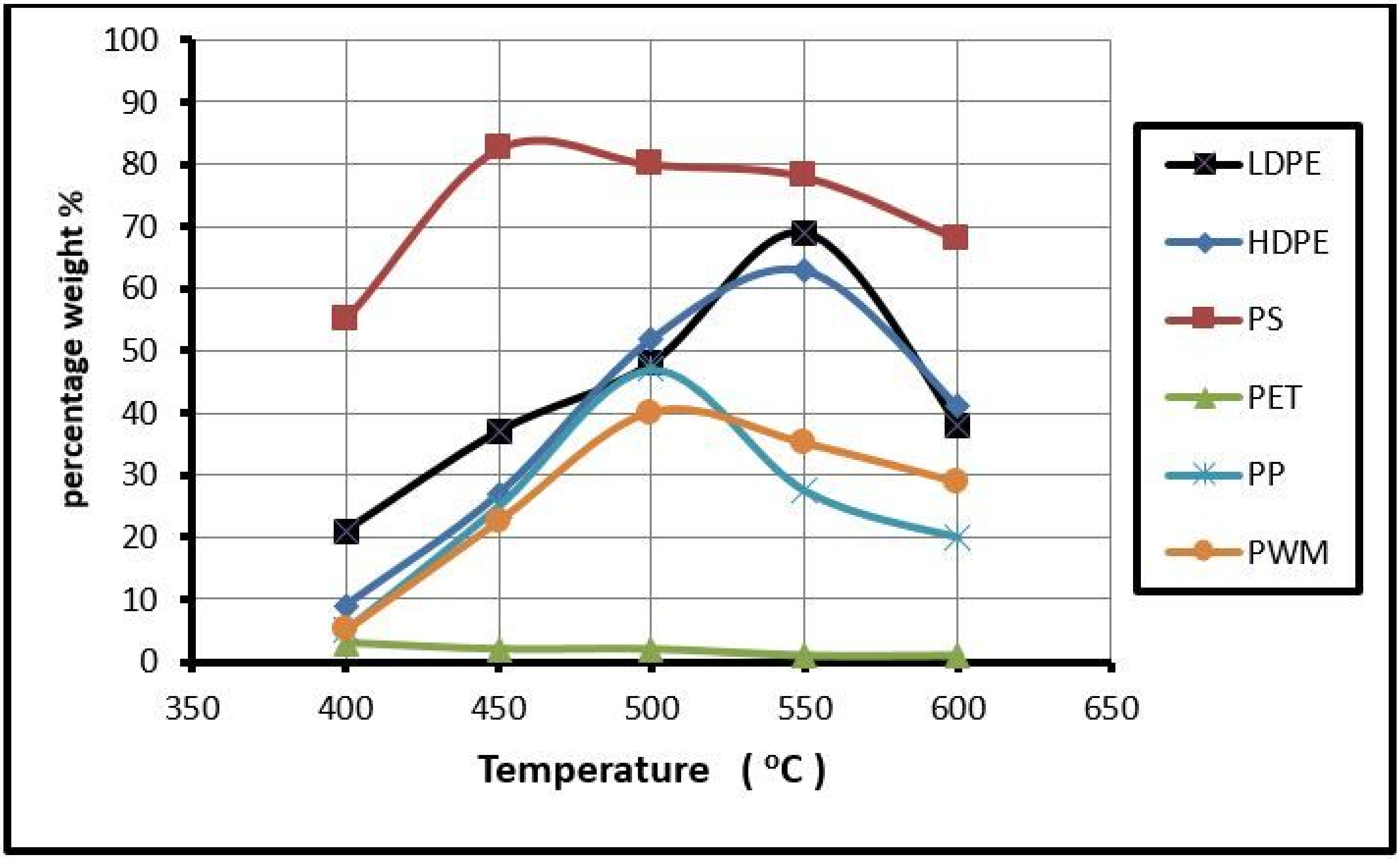

Figure 8

temperature versus oil yield from each plastic type.