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Developing a Simple Catalytic Pyrolysis Unit for Domestic Use

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ABSTRACT

The objective of this research is to develop a household catalytic pyrolysis unit for the thermal cracking of plastic wastes in Egypt, with a capacity of 5 kg. This unit is utilized to convert waste plastic into valuable oil through catalytic pyrolysis, using a low-cost Egyptian natural catalyst. The domestic pyrolysis unit is built from simple local materials. The reactor is a vertical tube reactor with a stainless-steel tube that has a 20 cm inner diameter, and a length of 40 cm. The initial cost of the unit is \$100. The Waste Polypropylene (WPP) was thermally and catalytically degraded at a temperature of 500°C using natural kaolin as a catalyst in various ratios of catalyst to plastic, i.e. 1:1, 1:2, 1:4, 1:6, and 1:8. Thermogravimetric analysis (TG) was utilized to analyze WPP's thermal degradation behavior, while X-ray fluorescence (XRF) testing was used to examine the catalyst. The produced oil was tested using gas chromatography-mass spectrometry (GC-MS). Pyrolysis of WPP without a catalyst produced 70% liquid oil by weight, while a 1:2 ratio of kaolin to plastic yielded the highest output at 80.75%. Using this catalyst increased the proportions of gasoline and kerosene, with essential oil making up 45%. The cost of the yearly produced oil is equal to 231\$/y, and the running cost of the unit is equal to 30\$/y. The annual profit from the produced oil is \$201, leading to a payback period of 0.5 years. Overall, this technique offers an eco-friendly solution that boosts family income and provides a sustainable energy source for the Egyptian community.

1. Introduction

The continuous global technological advancements have led to a rise in energy consumption, causing the depletion of fossil fuel reserves and increased environmental damage from gas emissions [1]. Fossil fuel supply is expected to steadily decline after 2042, making it crucial to develop new sustainable forms of energy [2]. Synthetic polymers, like household plastics, often end up in landfills or are incinerated due to the lack of technology for preparing the waste material for reuse [3]. Egypt's growing population and rising life requirements have led to the consumption of large amounts of plastic [4]. Plastic materials are used in numerous applications due to their lightweight, inexpensive, durable, and versatile nature [5]. The lack of sufficient waste management methods to dispose of

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plastic waste has resulted in serious environmental problems [6]. Egypt is the largest plastic polluter in the Arab world, producing 5.4 million metric tons of plastic yearly. A report by Worldwide Life in 2019 revealed that Egypt is the most significant source of Mediterranean plastic pollution [7, 8].

The global use of plastic is mainly composed of 35% polyethylene (PE), 23% polypropylene (PP), 13% polyvinyl chloride (PVC), 10% polystyrene (PS), 7% polyethylene terephthalate (PET), and 12% other polymers. The most common plastics found in waste are PE, PP, and PS [9]. Polypropylene is a versatile polymer known for its excellent mechanical characteristics, low density, and outstanding chemical resistance. It is used in various products, including furniture, pipes, office folders, storage boxes, computer chips, medical bottles, generic containers, and in the auto sector [10]. Plastics are not biodegradable and can persist in the environment for a long time [11]. Consequently, there are significant quantities of waste plastics in landfills with minimal degradation [12,13]. Recycling plastic waste is a critical issue to reduce landfill buildup. Plastic waste can be recycled into valuable products such as liquid and gas fuels through a process called pyrolysis, which involves the thermal cracking of long hydrocarbon chains into shorter-chain molecules at high temperatures of 300°C to 800°C without oxygen [14-17]. The gas produced by plastic pyrolysis has a high calorific value due to the presence of hydrogen, ethane, methane, butane, and propane, while the produced liquids can be used as an alternative to conventional fuel. Plastic waste is considered a sustainable source of fossil fuels because of its high calorific value compared to diesel and gasoline [18, 19]. Catalysts are used in plastic pyrolysis to improve product selectivity and distribution and to produce liquid oil with properties comparable to conventional fuels like diesel and gasoline [20].

1.1 Influence of Catalysts on Plastic Pyrolysis

Over the past decade, plastic waste pyrolysis has been conducted using a variety of catalysts. There are three main groups of catalysts: zeolite, silica-alumina, and fluid catalytic cracking (FCC) which are used in plastic pyrolysis [21]. Susastriawan and Sandria [22] used zeolite catalysts to catalytically pyrolyze polyethylene and found that the production of the liquid fraction increased as the zeolite size decreased, and the temperature increased. Onwudili et al. [23] studied the catalytic pyrolysis of various polymers using catalysts such as ZSM-5 zeolites Y, and FCC. It is reported that there is a decrease in the liquid fraction yield, but an increase in the quantity of aromatic compounds present. The quality of the oil fraction improved, making it suitable as a fuel. López et al. [24] used red clay and zeolite catalyst in waste plastic pyrolysis. Red clay was observed to require a more temperature than zeolite in pyrolysis to get a catalytic effect. The products obtained at 440°C in the case of using red clay as a catalyst can be compared with those obtained without using a catalyst at 500°C, such that the quantity of oil and gases produced are larger as well as the percentage of the aromatic substances in the produced liquids.

From this review of the literature, it can be concluded that there are three different types of catalysts that can be employed in the cracking of plastics: silica-alumina, zeolite, and FCC catalysts, and the oils produced using these catalysts by the pyrolysis process had characteristics approaching those of conventional fuel oils. Although these catalysts work effectively, their application is not practical because of the high manufacturing costs and significant process sensitivity to catalyst prices [25]. Therefore, the effect of a low-cost catalyst was studied in the pyrolysis process of waste plastic. Eldahshory et al. [26] investigated the effect of Three natural Egyptian catalysts, i.e. Kaolin, Hematite, and white sand on the cracking of WPP. It has been concluded that using a Kaolin catalyst produced the highest oil, i.e. 80.75% by weight. The oil produced by catalytic pyrolysis of WPP using kaolin had the lowest heavy oil content, and the highest light oil content. In addition, the kaolin catalyst increased the proportion of gasoline and kerosene in the produced oil. Kaolin is a cost-effective catalyst that improves the quantity and quality of the produced oil.

The objective of this project is to develop a simple home pyrolysis unit for mixed plastic waste, addressing the significant problems caused by plastic waste, and changing Egyptian attitudes towards domestic plastic waste. It is intended to create an added value from plastic waste that allows households to earn money, protect the environment, increase their income and contribute to the national sustainable development. The main objective of this project is to achieve the highest yield and quality oil through the conversion of household mixed plastic waste using a low-cost natural catalyst, as well as to establish a national technology for producing biofuels from domestic plastic waste. The WPP was thermally and catalytically degraded at a temperature of 500°C using natural Kaolin as a catalyst. Various ratios of catalyst to plastic were tested, including 1:1, 1:2, 1:4, 1:6, and 1:8, and the feasibility of the unit was examined.

2. DOMESTIC PYROLYSIS UNIT

In this study, a basic household catalytic pyrolysis unit is designed for the thermal cracking of a maximum of 5 kg of plastic waste. This unit is utilized to convert waste plastic into valuable oil through catalytic pyrolysis, using a low-cost Egyptian natural catalyst, i.e. Kaolin. The pyrolysis unit setup includes a nitrogen source, PID controller, electrical heater furnace, pyrolysis reactor, K-type thermocouple, condensing unit, and oil collector, as shown in **Fig. 1**. The domestic pyrolysis unit is built from simple local materials, and it consists of a 2-kW electrical heater furnace that is constructed using refractory fire bricks of thickness 10 cm, and it is externally insulated using mineral wool, which is cladded with aluminum sheets. The external dimensions of the furnace are 0.5m× 0.5m× 0.6m. The reactor is a vertical tube reactor, with a stainless-steel tube with a 20 cm inner diameter, and a length of 40 cm. The temperature of the reactor is controlled via a PID controller, thermocouples and a Variac transformer, which adjust the heating rate based on the set temperature. Nitrogen is pumped through the reactor with a flow rate of 80 mL/min during the pyrolysis process, in order to maintain an oxygen-free atmosphere, as shown in **Fig. 1**. A photo of the developed domestic pyrolysis unit is shown in **Fig. 2**, with an image showing the electric heater and the reactor pipe, also the burning of the produced methane gas during the pyrolysis process.

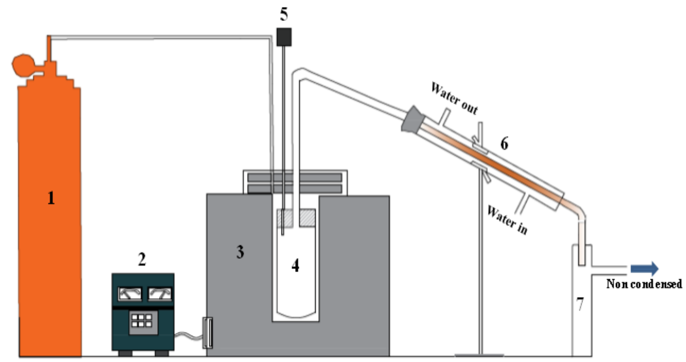

Fig. 1. The **domestic** Pyrolysis **unit**'s schematic diagram, where (1) Nitrogen bottle, (2) PID controller, (3) Electrical heater, (4) Pyrolysis Reactor, (5) Thermocouple, (6) Condensing unit, and (7) Oil collector.

Fig. 2. Construction of the domestic pyrolysis unit, where (a) Electrical heater installation, (b) furnace from inside, (c) installation of furnace, (d) Combined domestic unit, (e) Produced oil, (f) Non condensed gas.

2.1. WPP and Catalyst Preparation

Waste polypropylene (WPP) was utilized in the catalytic pyrolysis process, and it was obtained from Henkel Company for waste Plastic Collecting in Egypt [27]. The WPP was cleaned, dried, and then crushed into smaller pieces of 3-5 mm for the thermal gravimetric test and the pyrolysis experiments. The natural kaolin was examined, which was collected from Aswan city in Egypt. the catalyst was ground to a fine powder using a ball mill for 5 hours, such that the grain size of the final powder is less than 100 nm, and then was heated in a muffle for three hours at 500°C for thermal activation. Afterwards, the catalyst was characterized using the XRF analysis.

2.2. Experimental Procedure

The WPP and catalyst are added to the pyrolysis reactor, then the reactor is heated to 500°C at a rate of 5°C/min and is maintained at that temperature for 30 minutes until the process is finished. The gaseous products are condensed at room temperature using a condenser that is attached to the reactor's outlet. The liquid that has condensed is collected, and a gas bag is used to collect the uncondensed gases. Finally, the mass balance method is used to calculate the gas production after weighing the collected liquid and the char that has been deposited in the reactor [28]. The following equations were employed to calculate the mass proportion of oil, char, and non-condensable gases.:

$$\text{Percentage of oil yield, Oil (wt.\%)} = \frac{\text{Mass of Oil}}{\text{Mass of WPP}} \times 100 \quad (1)$$

$$\text{Percentage of char yield, Char (wt.\%)} = \frac{\text{Mass of Char}}{\text{Mass of WPP}} \times 100 \quad (2)$$

Percentage of gas yield, Gas (wt.%) = 100 - (Oil% + Char%) (3)

2.3. Characterization

2.3.1. Characterization of WPP

To investigate the thermal decomposition behavior of WPP, thermogravimetric (TG) and differential thermal (DT)analysis measurements were taken using a thermogravimetric analyzer (SDT Q600 USA). With Dynamic Temperature Precision ±0.5°C In a pure nitrogen atmosphere, WPP was heated from room temperature to 1000°C at a rate of 10°C/min. TG and DTG curves for the Pyrolysis of waste polypropylene using nitrogen gas with a heating rate of 10°C/min are shown in **Fig. 3**. It can be seen from **Fig. 3** that the maximum weight loss was at 465°C due to the thermal decomposition of PP. The DTG curve shows that the thermal decomposition starts at 410°C, and the maximum decomposition rate occurs at 468°C. The pyrolysis process ends completely by turning WPP into gases at a temperature of 485°C [29].

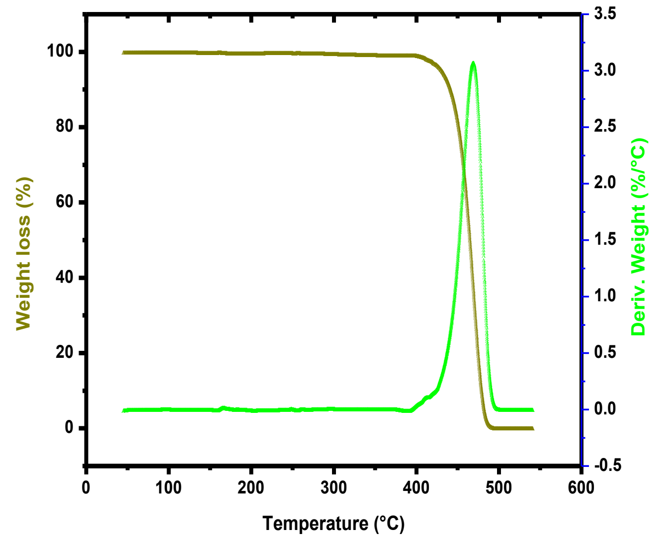

Fig. 3. Temperature gradient (TG) and differential thermal (DT) curves for WPP.

2.3.2. Characterization of catalysts

The technical composition of Kaolin was identified by XRF, and the outcomes are shown in **Table 1**. The identified elements were supplied as a percentage of the elements in the overall sample that are represented as oxides. It was observed that the majority of the compounds in the Kaolin sample are silicon oxide (SiO_2) and aluminum oxide (Al_2O_3), however there exist trace levels of many other oxides.

Table 1. Percentage of chemical composition of the Kaolin catalyst used in the pyrolysis of WPP.

Catalyst / Oxides %	Kaolin
SiO_2	60.06
Al_2O_3	29.52
Fe_2O_3	5.33
CaO	0.33

MgO	0.33
SO_3	0.47
K_2O	0.39
Na_2O	0.15
TiO_2	2.08
Cl	0.01
LOI	1.22

2.3.3. Characterization of oil

The oil produced by the pyrolysis process was qualitatively estimated using the GC-MS. GC system 7010B GC/TQ inert mass spectrometry with triple Axis had been used for the analysis of matched chromatogram peaks. The carrier gas utilized was Helium. The Wiley Registry/NIST Library was used to identify the peaks with the highest probability and quality of greater than 80%.

3. EXPERIMENTAL RESULTS

3.1 Yield of Products

The results of the non-catalytic pyrolysis of WPP and the product yields from pyrolysis of WPP with different ratios of Kaolin catalyst to WPP are presented in **Table 2**.The yield of oil due to non-catalytic pyrolysis of WPP was 70 wt.% of liquid oil, 24.3 wt.% of gas and, 5.7 wt.% of solid char. Various ratios of catalyst to plastic were tested, including 1:1, 1:2, 1:4, 1:6, and 1:8. As the Kaolin to WPP ratio increases from 1:8 to 1:2, the liquid yield increased from 74.4 wt.%. to 80.75 wt.%., while the gas yield decreased from 23.52 wt.%. to 17.55 wt.%. The Kaolin to WPP ratio of 1:2 resulted in the highest yield of liquid oil, i.e., 80.75 wt.%. The oil yield was reduced to 78.33 wt.% as a result of the catalyst to plastic ratio being increased further to 1:1. This indicates increasing or decreasing the Kaolin to WPP ratio from 1:2 will decrease the oil yield and increase the gas yield, i.e., Kaolin to WPP ratio of 1:2 is the optimum for oil yield. The rise in liquid yield due to using Kaolin as a catalyst represents a significant improvement in the thermal cracking of WPP, and that is due to Kaolin's acidity, mesoporous surface area, and high Si/Al ratio [30]. Where, adding Al_2O_3 to Silica, which is the case of using Kaolin as a catalyst, has improved the oil yield a lot compared to the no catalyst, as can be seen in **Table 2**. Therefore, it is highly recommended to study the influence of Al_2O_3 to Silica ratio on the oil yield and quality during the catalytic pyrolysis of WPP, in order to determine the optimum ratio.

Table 2. Product's yield (wt.%) due to pyrolysis of WPP at various ratios of Kaolin catalyst to WPP and non-catalytic pyrolysis of WPP.

Yield (wt.%) / Catalyst	Kaolin: WPP	Oil	Gas	Char
No catalyst	----	70	24.3	**<u>5.7</u>**
Kaolin	1:1	78.33	20.02	1.65
	1:2	**<u>80.75</u>**	17.55	1.7
	1:4	79	19	2
	1:6	76.67	21.33	2
	1:8	74.4	**<u>23.52</u>**	**<u>2.08</u>**

3.2 Quality of Oil

The highest yield of oil from the catalytic pyrolysis of WPP has been analyzed using the GC-MS analyzer, and the results are presented and discussed in this section. The number of carbon atoms of the produced oil from the catalytic and non-catalytic pyrolysis of WPP is presented in **Fig. 4** and **Table 3**. It can be concluded from **Table 3** that the produced oil in case of non-catalytic pyrolysis of WPP had a big percentage of heavy oils, i.e. $C > C_{15}$. However, using kaolin during the pyrolysis of WPP has decreased the percentage of heavy oils, and increased the percentage of light oil, i.e., C_5-C_{10}, as well as the average weight oil, C_{11}-C_{15} [31], as can be seen in **Table 3**.

Using Kaolin in the catalytic pyrolysis of WPP produced oil with the lowest percentage of heavy oil, i.e., 25.98%, and the highest percentage of light oil, i.e., 25.37%. Therefore, it can be concluded from **Table 3** that if the objective of the pyrolysis process is to produce light weight hydrocarbons, then it is better to use Kaolin catalyst in the catalytic pyrolysis of WPP. The weight percentage of produced oil from the non-catalytic and catalytic pyrolysis of WPP has been classified according to the fuel group, i.e., gasoline (C_4-C_{12}), kerosene (C_{10}-C_{18}) and diesel (C_{12}-C_{23}) [32], and the results are presented in **Fig. 5**. Therefore, it can be concluded from **Fig. 5** that the Kaolin catalyst has increased the percentage of gasoline and Kerosene in the produced oil in comparison to the non-catalyst case, which promotes the Kaolin catalyst to be used for the pyrolysis of WPP if the objective is light oils like gasoline and kerosene.

Table 3. The weight percentage of the produced oil according to the Carbon atom number as a function of the type of catalyst, based on the GC–MS analysis.

Carbon number range / Catalyst	Weight % of C_5–C_{10}	C_{11}–C_{15}	> C_{15}
No catalyst	**15.06** (Lowest)	26.68	**58.26** (Highest)
Kaolin	**25.37** (Highest)	48.65	**25.98** (Lowest)

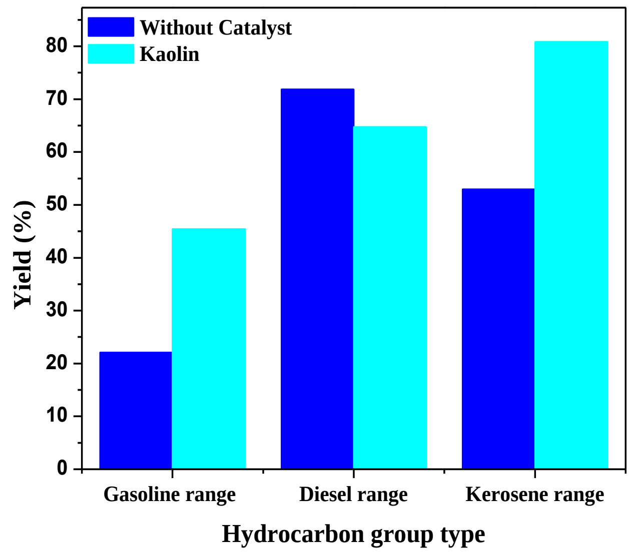

Fig. 5. Weight percentage of the produced oil from the non-catalytic and catalytic pyrolysis of WPP as a function of the fuel group, i.e., gasoline (C_4-C_{12}), Kerosene (C_{10}-C_{18}) and diesel (C_{12}-C_{23}).

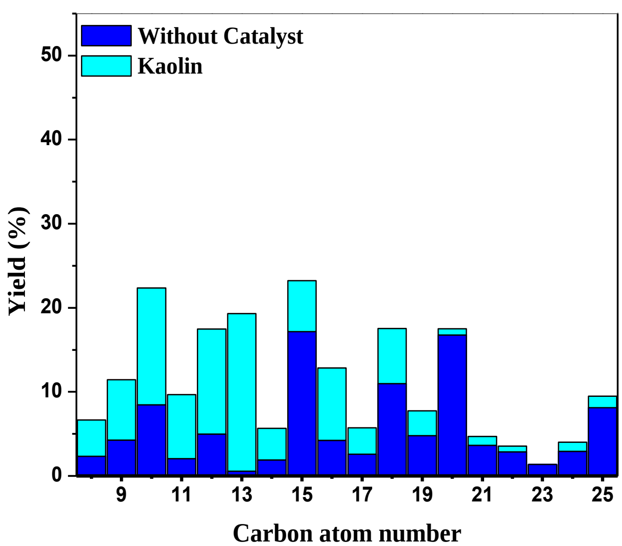

Fig. 4. Carbon atom number of produced oil from non-catalytic and catalytic pyrolysis of WPP.

The produced oil from the non-catalytic and catalytic pyrolysis of WPP is a combination of hydrocarbons having carbon atoms ranging from C_5 to C_{25}. The composition of the produced oil because of WPP's non-catalytic and catalytic pyrolysis in terms of the aliphatic (alkanes, alkenes, cycloalkanes) and aromatics groups are presented in **Table 4** [33]. It can be concluded from **Table 4** that adding Kaolin to the WPP during the pyrolysis process resulted in the production of oil with the highest percentage of aromatic oil, i.e., 45%, and the percentage of aliphatic oil was highest, i.e., 80%, in case of non-catalytic pyrolysis. As a result, adding Kaolin to the WPP during the pyrolysis process enhances the oil's quality, i.e., it produces lighter aromatic oil with a high percentage of gasoline range.

Table 4. Oil composition of non-catalytic and catalytic pyrolysis of WPP.

Oil composition Yield (wt.%) / Catalyst	**Aliphatics**	**Aromatics**
No catalyst	**80**	**20**
Kaolin	**55**	**45**

3.3 Feasibility Study of the domestic unit

The presented feasibility study is based on each household produces 5 kg of waste plastic per week, therefore the yearly plastic waste is about,

Household yearly plastic waste =

$$5\frac{\text{kg}}{\text{week}}\times 52\frac{\text{week}}{\text{y}}=260\frac{\text{kg}}{\text{y}}.$$

It can be concluded from the presented domestic unit that the amount of oil produced from the pyrolysis of 5 kg of waste plastic is about 4 kg of oil, i.e. 80 percent of the input waste is converted into oil, and based on the current international prices of heavy oil, i.e. 1 $/lit [34], therefore, the cost of the yearly produced oil is,

$$\$\text{Oil}=260\frac{\text{kg}}{\text{y}}\times 0.8\times\frac{\text{lit}}{0.9\text{kg}}\times 1\frac{\$}{\text{lit}}=231\frac{\$}{\text{y}}.$$

The running cost of the unit is equal to the consumed electrical energy, nitrogen bottles and the catalyst price, and these are all presented in **Table 5**, which is in total equal to 30$/y. Therefore, the annual net profit of the unit is 231-30=201 $/y, and the Return of Investment (ROI) is equal,

$$\text{ROI}=\frac{InitialCost}{Annualnetprofit}=\frac{100\$}{201\frac{\$}{year}}=0.5year.$$

Therefore, it can be concluded based on ROI that each half year the household earns his capital cost besides saving the environment and contribute to national sustainable development.

Table 5. Yearly running costs

	Amount	Price	Annual cost
Electricity	2 kW×2h/w×52w/y= 208kWh/y	0.08$/kwh	16 $
Nitrogen	1 bottle per year	6 $/bottle	6 $
Catalyst	20 Kg/y	0.4 $/kg	8 $
Total			30 $

4. CONCLUSIONS:

The objective of this project is to develop a simple home pyrolysis unit for mixed plastic waste to address the significant problems caused by plastic waste and change Egyptian attitudes towards domestic plastic waste. The main objective of this project is to achieve the highest yield and quality oil by converting household mixed plastic waste using a low-cost Egyptian natural catalyst and establishing a national technology for producing biofuels from domestic plastic waste. It can be concluded from the performed research that;

1. WPP produced an oil yield of 70% liquid oil, 24.3 wt.% gas, and 5.7 wt.% solid char as a result of non-catalytic pyrolysis.
2. The highest oil yield was obtained at a ratio of 1:2 of the Kaolin catalyst to plastic, i.e., 80.75 wt.%.
3. Using Kaolin in the WPP catalytic pyrolysis produced oil with the lowest percentage of heavy oil, i.e., 25.98%, and the highest percentage of light oil, i.e., 25.37%.
4. Kaolin catalyst has increased the percentage of gasoline and Kerosene in the produced oil.
5. The highest proportion of aromatic oil was obtained by using Kaolin in the catalytic cracking of WPP, i.e., 45%.
6. The profit of the produced oil per year is 201$ and the revenue time of the domestic unit is 0.5 years.
7. The developed unit for the Egyptian community is a promising technique since it saves the environment, increases the income per family and can be treated as a sustainable source of energy.

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