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## ENHANCING THE PYROLYTIC GAS PRODUCTION GENERATED BY SLOW PYROLYSIS USING A FIXED-BED PROLYZER

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**ABSTRACT:** The biomass slow pyrolysis using the fixed-bed pyrolyzer is a simple and inexpensive technique that can be used in small farms comparing to the complex and expensive technology of the fast pyrolysis. However, slow pyrolysis primary produces bio-char and lower yields of bio-oil and pyrolytic gas. Thus, there is urgent need to enhance pyrolytic gas production under the slow pyrolysis conditions on the account of bio-char due to the advantage of using the gas in wide applications in farm. Hence, this work aims to fabricate and operate a small-scale fixed bed pyrolyzer to enhance the pyrolytic gas productivity from the ground pieces of Mango trees Pruning Logs (MPLs) under slow pyrolysis conditions (heating rate of 0.01-1 °C/s, vapor residence time of 4 min.) and full absence of oxygen. The pyrolytic gas production was investigated under different final pyrolysis temperatures of 300,350 and 400°C, particle length ranges of 1-5, 10-15 and 20-25 mm. The obtained results revealed that, the increase of pyrolysis temperature from 300-400°C and decrease of the ground MPL length from 20-25 to 1-5 mm was accompanied with explicit increment in the pyrolytic gas concentration, gas yield, higher heating value of pyrolytic gas (HHV<sub>g</sub>) and energy conversion efficiency by about 34.28%, 61.15%, 12.68% and 66.10%, respectively along to high concentrations of the combustible gases (*e.i.* H<sub>2</sub>, CH<sub>4</sub>). Additionally, the optimal cost per energy unit of pyrolytic gas (0.085 EGP/MJ or 0.005 \$/MJ) is lower than cost per energy unit of the natural gas and LPG by about 11.45% and 75.07%, respectively.

**Key words:** Slow pyrolysis, Fixed-bed pyrolyzer, Mango trees pruning logs, Pyrolytic gas, Heating value, Energy conversion efficiency, cost analysis

## INTRODUCTION

In Egypt , large quantities of agricultural waste are produced annually about 83.991 mega ton including rice straw, throne and wood of a lot of crops and trees as the percentage of wood 35.66%, most of which contain tremendous amounts of energy, but unfortunately most of these wastes are poorly handled according to **The Ministry of Environment in Egypt (2017)**.

Nowadays, there is an increasing need for renewable energy demands to address the increased fuel prices and the decline of petroleum goods with a growing population. A promising solution for these challenges is green energy, especially biomass. Consequently, this would reduce the environmental threats arising from fossil fuels; in particular, the high levels of

nitrogen oxides, carbon dioxide, and sulphur oxides (**Mangut *et al.*, 2006**).

For the rural population in Egypt, biomass is a significant energy supply that includes farm residues and dry animal dung cakes that are directly burnt in rudimentary stoves and ovens to provide households with thermal energy for cooking, baking, water and space heating purposes (**Abd Allah *et al.*, 2016**), resulting in multiple environmental problems like the black cloud (**Hamdy, 1998**). Due to these activities, Egypt has been ranked among the eleven countries that are the fastest growing greenhouse gas emissions (**Egypt Climate Investment Funds, 2017**).

Over the past few years, many countries all over the world have succeeded to utilize the available resources as biomass feedstock to

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generate thermal and electricity power, then Egypt has potential sources of biomass that enable it to become one of those countries (**Abd El-Sattar *et al.*, 2019**).

Globally, exploiting the agricultural residues such as; cassava stalk, cassava roots, corn stalk and leaves (**Yokoyamaa *et al.*, 2000**); oil palm biomass (**Sukiran *et al.*, 2016**); rubber wood (**Shariff *et al.*, 2016**); corn cobs, wheat straws, rice straws and rice husks (**Biswas *et al.*, 2017**); wood sawdust (**Mishra and Mohanty, 2018**). Accordingly, it is obvious that literatures about exploiting the pruning residues of orchard trees as biomass source to generate bio-fuels by pyrolysis is not found or very scarce. However, wheat straw, rice straw, cotton stalks, corn stover and bagasse or even rice hull are very common to be used in Egypt as biomass feedstock for generating bioenergy and it may use for animal feed and bedding, but the utilization of the fruit trees pruning residues is very rare (**Tawfik and El-Didamony, 2017**).

The thermochemical conversions of biomass can be carried out via liquefaction, combustion, gasification, carbonization and pyrolysis (**Diebold, 2000**). Particularly, pyrolysis is the thermal decomposition process that occurring in the full absence of oxygen, which has a great potential in converting biomass into high energy density Products including: bio-oil, bio-char, and pyrolysis gas (**Kan *et al.*, 2016**). So, the biomass pyrolysis has the advantages of producing three forms of the bio-fuels as different percentages according to the input parameters comparing to the other thermochemical conversion process that represents in the gasification process which gives the producer gas/ syngas as a sole form of bio-fuel (gaseous form).

Bio-oil or pyrolytic oil with an appropriate water content can be used directly as fuel in boilers, upgraded into fuel for internal combustion engines, or turned into a high-value product for food and chemical processes (**Bridgwater, 2012; Bridgwater and Peacocke, 2000**). Besides, the bio-char and pyrolytic gas can be used as biofuels to generate heat or power for use in pyrolysis or other processes (**Palamanit *et al.*, 2019**). There is no need to post-treatments for both of bio-char and pyrolytic gas and they can be utilized directly as heat source through the direct burning. On the contrary, the bio-oil needs

to be subjected to hydrocracking for producing gasoline and diesel because this oil is not self-igniting like fuel oil, and as such it cannot be blended with diesel for operating a diesel engine (**Basu, 2010**). Generally, the quantity and quality of pyrolysis bio-products are depending on the type of pyrolysis technology, pyrolyzer as well as biomass type and its properties (**Guedes *et al.*, 2018; Leng and Huang, 2018; Chen *et al.*, 2019**). The bio-product of pyrolysis depends on the design of the pyrolyzer, the physical and chemical properties of the biomass feedstock and important operating parameters including the heating rate, pyrolysis temperature and residence time inside the pyrolyzer which can alter the bio-product yield of pyrolysis in the three forms of solid, liquid and gas (**Basu, 2010**). Elucidating the effect of some reaction factors such as; heating rate, the carrier gas, pyrolysis temperature and pyrolysis medium etc. together with other factors such as; biomass particle size and the catalyst on the pyrolysis process is very essential to be investigated (**Yao *et al.*, 2017**).

The present work aims to exploit one of the potential biomass feedstock that represents in mango tree pruning log (MPL) due to its abundant availability in Egypt, and in the meantime the scarcity of previous literature about utilization of such biomass feedstock as a source of renewable energy. Generally, Egyptian farms produced about 30 Mega ton annually of agricultural residues where fruit tree pruning contribute with 12.3% of total national residues (**FAO, 2017**). Sharkia governorate came in the third place of area and national production of mango, where the area of mango reached to 34267 feddan (14392.14 ha) and the production achieved 173698 ton, according to (**CAPMAS, 2018**). Thus, the mango pruning residues is abundant, but unfortunately no recent or previous attempts to be used in different purposes except the direct incineration which would elevate the green house gases (GHG) emissions. Hence, there is an urgent need to exploit this potential hydrocarbon feedstock of MPL by using a clean, sustainable and environment-friendly method represented in the pyrolysis process. Furthermore, it is essential to promote and develop an inexpensive pyrolysis technique to generate bio-fuels from the

lignocellulosic residues instead of the complex fast and/or flash pyrolysis for domestic applications in the small farm such as; cooking, heating etc.

From the economic aspect, the slow pyrolysis is considered the most suitable technology for small farmers to convert their lignocellulosic residues to bioenergy using the most affordable small-scale type of pyrolyzers represents in the fixed-bed pyrolyzer in batch mode.

Slow pyrolysis can be programmed to produce slightly more bio-char (50%) along with organic gases, but it takes hours to finish (Dahariya, 2013). The major drawback of any pyrolysis process, that the biomass decomposition in this type of thermochemical conversion needs a continuous external source of heat. Thence, this work is focused on fabricating and performance evaluation of a local made fixed bed pyrolyzer taking into consideration the simplicity of design, easiness for operation and maintenance for improving the pyrolytic gas productivity under slow pyrolysis conditions that mainly forms bio-char in terms of productivity, thermal efficiency using the mango trees pruning residues. Thus, the present study may consider as an attempt to improve the yield of pyrolytic gas on the account of bio-char to utilize a portion of this gas in the pyrolyzer's burner to heat the pyrolysis chamber as a continuous heat source instead of using fossil fuel in purpose of sustainability and environment protection. Moreover, an economic analysis for the proposed system was done to estimate the cost per unit of generated pyrolytic gas energy and it compared to cost per unit of some fossil fuels.

## MATERIALS AND METHODS

The practical experiments were carried out in 2020 at Faculty of Agriculture farm, Zagazig University, Egypt.

### Mango Trees Pruning Logs Characteristics

In this work, the naturally dried of Mango trees Pruning Logs (MPL) were used as biomass feedstock. MPL were chopped in form of pieces with length varied from 1-5, 10-15 and 20-25 mm using electrical chopping machine. The proximate, ultimate and chemical analysis was performed to determine the gross and elemental compositions of

the MPL pieces, as shown in Table 1. Where the proximate, chemical and ultimate analysis were carried out in the animal production laboratory, biochemistry lab and central lab, respectively at Faculty of Agriculture, Zagazig University. The prepared biomass samples were kept in sealed plastic bags prior to the experiments (Sakulkit *et al.*, 2020) and to be ready for the Proximate, ultimate and chemical analysis.

### Experimental Setup

Fig. 1 depicts the proposed prototype fixed-bed pyrolyzer that mainly consists of a fixed-bed pyrolysis unit, cooling serpentine, bio-oil collector and N<sub>2</sub> gas cylinder.

The fixed-bed pyrolysis unit is made in cylindrical shape using galvanized iron sheets which consists of two chambers namely; the Pyrolysis and burner chambers. The external surface of the pyrolysis unit is wrapped with 47 mm appropriate thickness of glass wool as insulating material. This unit is carried on three iron trestles at height of 40 cm above the ground. The pyrolysis chamber occupied the most of the fixed-bed pyrolysis unit enclosure which the pyrolysis process being carried out. The bottom of this chamber is provided with a solid iron gate to be used as the bed of feedstock. The burner chamber represented the rest of the cylindrical enclosure of the fixed-bed pyrolysis unit, which is allocated beneath the pyrolysis chamber to supply the heat energy to the feedstock's bed. The burner chamber contains gas stove burner that being supplied with required gas by LPG cylinder by rubber hose to heat up the solid grate and start the pyrolysis process. The peripheral surface of the burner chamber provided with slots to allow the required amount of oxygen to enter the chamber for burning the LPG. The pyrolysis chamber has a restricted lid at the top provided with thermal gasket to facilitate the loading of chamber with feedstock. Three temperature ceramic sensors (K-type) were penetrated the reaction chamber wall to determine the pyrolysis temperature. The pyrolyzer's enclosure completely purged from air by supplying pressurized N<sub>2</sub> gas with high purity (99.99%) using N<sub>2</sub> gas cylinder. Accordingly, the oxygen would be expelled out from the pyrolysis chamber before starting experiments through a vertical tube with controlling valve located next the lid at top side of chamber,

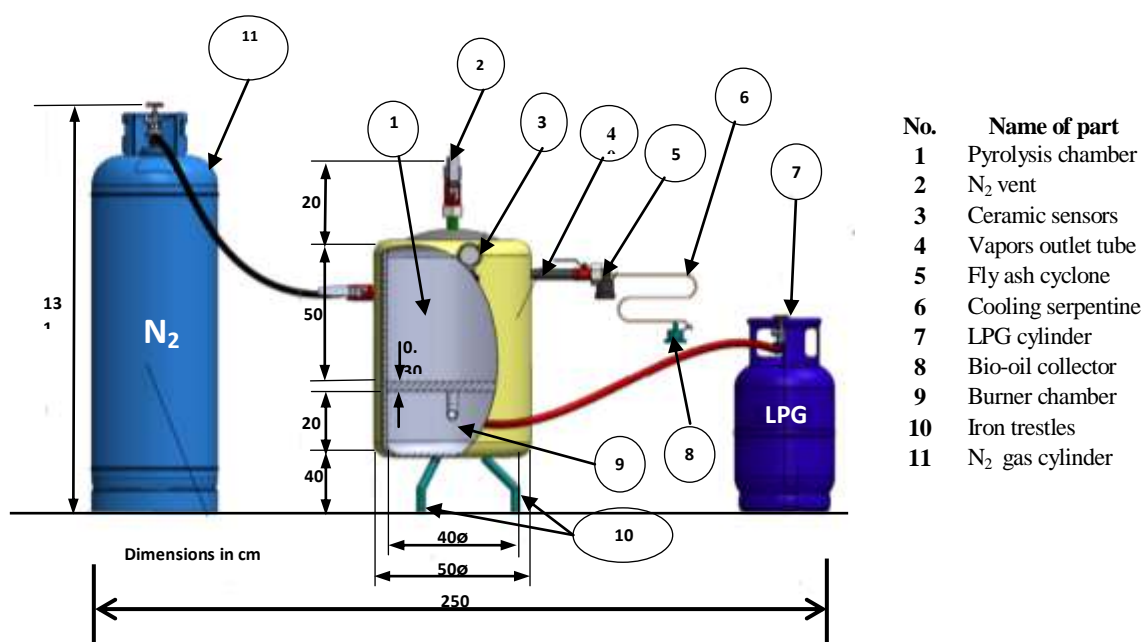
**Table 1. Proximate, ultimate and chemical analysis of the ground MPL**

Proximate analysis (wt %db*)	Ultimate analysis (wt % db*)	Chemical analysis (wt %db*)	
Moisture content <sup>a</sup> (M.C)	10.93± 0.05	Carbon <sup>a</sup> 54.24± 0.20	Hemicellulose <sup>a</sup> 27.5± 0.11
Total solids <sup>a</sup> (TS)	89.07±0.03	Nitrogen 0.14	Cellulose <sup>a</sup> 39± 0.08
Fixed carbon <sup>a</sup> (FC)	23.49± 0.40	Hydrogen <sup>a</sup> 5.80± 0.15	Lignin <sup>a</sup> 26.90± 0.05
Volatile matter <sup>a</sup> (VM)	69.74± 0.25	Oxygen <sup>a</sup> 39.72± 0.02	**HHV <sub>b</sub> <sup>a</sup> (MJ/kg) 21.53± 0.04
Ash content <sup>a</sup> (A)	6.77± 0.02	Sulfur 0.10	

<sup>a</sup> values are means ± SD (n=3)

\*(wt % db) = weight percentage on dry basis

\*\* HHV<sub>b</sub> = higher heating value of biomass



**Fig.1. Schematic view of the proposed fixed-bed pyrolyzer**

which acts as N<sub>2</sub> vent that. Once the vapors resulted from the feedstock decomposition is gathered in the pyrolysis chamber, the valve outlet tube would open after certain time and allows these vapors to be directed to towards other units. The scrubbing cyclone is attached at the end of the outlet tube to extract the fly ash that may exit with the mixture of produced vapors due to the pyrolysis process, and then the vapors ready to be cooled by the cooling serpentine. A copper serpentine was connected to the outlet port of the scrubbing cyclone. It is

made of copper with an internal diameter of 13.87 mm, external diameter of 15.87 mm and separated by 10 cm interval distances. A by-pass tube was welded to serpentine and attached to the bio-oil collector.

### Experimental Procedure

The practical experiments in this work were run in a batch mode under slow pyrolysis condition. These conditions including low pyrolysis temperature (up to 400°C), heating rate in range of <0.01–2.0°C/s and relatively

long residence time for vapor in the reaction zone in range of 5-30min (Basu, 2010). For each batch trial, 1500 g of ground MPL was added to be pyrolyzed. Before starting each experiment, the pyrolysis chamber was closed by the lid strictly and heated to temperature of 97°C, then the biomass sample was fed to pyrolysis chamber and the lid closed again. Afterwards, the N<sub>2</sub> vent is open and considerable amount of N<sub>2</sub> gas was purged into the pyrolysis chamber enclosure to expel the air to the ambient through the N<sub>2</sub> vent, while the valve of the outlet vapors tube is remained close. Subsequently, the ground MPL sample was heated continuously in range of 0.01-1 °C/s until reaching the desirable reaction temperature of pyrolysis. The K-type ceramic thermocouples are plugged to a digital data logging thermometer-4 channels (TENMARS, TM747DU, Taiwan) to measure the reaction temperature with measuring range of -100 : 1300°C and accuracy of ± 0.1% rdg + 0.7°C.

Once the reaction temperature was reached, the heating of pyrolysis chamber was stopped and the pyrolysis vapor trapped for 4 min as residence time, then the valve of the outlet tube was opened to pass the pyrolysis gases to the cooling serpentine, then the condensable gases was turned into bio-oil in the collector, while the non-condensable gases were formed the pyrolytic gas, Meanwhile the bio-char was deposited on the solid grate within the pyrolysis chamber.

For each experiment, the flow rate (m<sup>3</sup>/h) of pyrolytic gas that received from the outlet port of the cooling serpentine was measured using a digital hot-wire air velocity meter (TENMARS, TM-4002, Taiwan) provided with probe.

A sample of the produced gas was collected in a rubber bladder used in earlier work of Atiya *et al.* (2017) and analyzed by Gas Chromatograph (Scion 456-GC, UK) to detect the pyrolytic gas components (H<sub>2</sub>, CH<sub>4</sub>, CO, CO<sub>2</sub> and other hydrocarbons) at the Egyptian Petroleum Research Institute (EPRI), Cairo, Egypt. The yields of bio-oil and bio-char were determined by weighing, and then the mass percentages of these yields are calculated by dividing the mass of each yield by the mass of the parent biomass.

## Experimental Variables and Determinations

Previous results showed that, the most thermal decomposition of biomass occurred at temperatures ranging from 200 to 400°C (Sakulkit *et al.*, 2020). Thus, the performance of the proposed pyrolyzer in this work was evaluated under the three set points considered as final pyrolysis temperature of 300, 350 and 400°C, different particle lengths of MPL in ranges of 1-5, 10-15 and 20-25 mm, using heating rate of 0.01-1°C/s and vapor residence in pyrolysis chamber of 4 minutes.

## Measurements

### Moisture content

The moisture content of the MPL was determined by drying three samples as replicates in an oven furnace at a temperature of 105°C for 24 Hours using relationship in Eq. (1) (Basu, 2010):

$$M.C = (M_w - M_d) / M_w \quad (\%) \quad (1)$$

Where M.C is the moisture content of sample (%), M<sub>w</sub> and M<sub>d</sub> is the sample mass before and after drying (g), respectively.

### Higher heating value of the biomass

The energy content of MPL was reported as the higher heating value (HHV<sub>b</sub>), which determined by using Eq. (2) given by (Channiwala and Parikh, 2002):

$$HHV_b = 0.3491 C + 1.1783 H + 0.1005 S - 0.1034 O - 0.0151 N - 0.0211 A \quad (\text{MJ/kg}) \quad (2)$$

Where C, H, S, O, N, and A are percentages of carbon, hydrogen, sulfur, oxygen, nitrogen and ash, respectively as determined by ultimate and proximate analysis on a dry basis.

### Higher heating value (HHV<sub>g</sub>) of the pyrolytic gas

The higher heating value of the pyrolytic gas can be estimated by the equation (3) as shown by (Suwannakuta, 2002).

$$HHV_g = 13.1 (\text{CO}\% / 100) + 13.2 (\text{H}_2\% / 100) + 41.2 (\text{CH}_4\% / 100), \text{ MJ/Nm}^3 \quad (3)$$

Where CO%, H<sub>2</sub>%, and CH<sub>4</sub>% are the volumetric percentages of carbon monoxide, hydrogen, and methane, respectively according to the pyrolytic gas analysis.

### Yield of the pyrolytic gas

According to equation (4) given by (Gai and Dong, 2012), the gas yield ( $G_y$ ) is calculated as the ratio of pyrolytic gas to the quantity of the parent dry biomass:

$$G_y = V_g / M_f, \text{ Nm}^3 / \text{kg}_{\text{Biomass}} \quad (4)$$

Where  $V_g$  is the gas flow rate ( $\text{Nm}^3/\text{h}$ ) and  $M_f$  is the quantity of the dry biomass ( $\text{kg}/\text{h}$ ).

### Energy conversion efficiency for pyrolytic gas ( $\eta_{c-g}$ )

In the light of Eqs. (2:4), the energy conversion efficiency for pyrolytic gas ( $\eta_{c-g}$ ) using the proposed pyrolyzer is defined by the ratio of the total amount of  $\text{HHV}_g$  of the gas to the  $\text{HHV}_b$  of the parent feedstock as depicted in following relation:

$$\eta_{c-g} = \left( \frac{\text{HHV}_g \times G_y}{\text{HHV}_b} \right) \times 100, \quad \% \quad (5)$$

### Life cycle cost (LCC) analysis for the proposed fixed-bed pyrolyzer

The life cycle cost analysis was carried out for the fixed bed pyrolyzer assuming useful life of 10 years. The capital cost for the fixed bed pyrolyzer was given in Table 2 according to 2020 prices.

Hence, cost per unit of generated pyrolytic gas energy was calculated for the fixed-bed pyrolyzer according to the following equations given by (Chel *et al.*, 2009):

#### Present maintenance cost

$$P_M = C_M \left[ \frac{((1+i)^{10} - 1)}{(i \times (1+i)^{10})} \right] \quad (6)$$

Where:

$P_M$ = Present maintenance cost (EGP).

$C_M$ = Annual maintenance and repairs cost (taken 1% of capital cost).

$i$  = Interest rate (taken 9.25% according to Egyptian Central Bank in 2020).

#### Present operating cost

$$P_O = C_O \left[ \frac{((1+i)^{10} - 1)}{(i \times (1+i)^{10})} \right] \quad (7)$$

Where:

$P_O$ = Present operating cost (EGP).

$C_O$ = Annual operating cost (LPG and nitrogen gas costs).

$i$  = Interest rate (taken 9.25% according to Egyptian Central Bank in 2020).

#### Net present cost

$$P_{\text{Net}} = P_{\text{FI}} + P_M + P_O - \left[ \frac{S}{(1+i)^{10}} \right] - \left[ \frac{BC}{(1+i)^{10}} \right] \quad (8)$$

Where:

$P_{\text{Net}}$  = Net present cost (EGP).

$P_{\text{FI}}$  = Capital cost (EGP).

$S$  = Salvage value of the system at the end of 10 years (taken 15% of capital cost) (EGP).

$BC$  = By-product value of bio-char at the end 10 years, EGP.

#### Annualized cost

$$A_A = P_{\text{Net}} \left[ \frac{(i \times (1+i)^{10})}{((1+i)^{10} - 1)} \right] \quad (9)$$

Where:

$A_A$  = Annualized cost of the system (EGP/Year).

#### Average Cost per unit of generated pyrolytic gas energy

$$C = \frac{A_A}{U} \quad (10)$$

Where:

$C$  = Cost per unit of generated pyrolytic gas energy by fixed bed pyrolyzer, (EGP/MJ)

$U$  = Total annual gained pyrolytic gas energy, MJ/year

In this study, the cost of the pyrolytic gas energy unit was compared with the actual cost of other types of energy using (Table 3).

## RESULTS AND DISCUSSION

### Effect of Pyrolysis Temperature and Feedstock Length on the Distribution of the Bio-Product Yields

The bio-products of pyrolysis are mainly consisted of bio-char, bio-oil and pyrolytic gas which depending upon the operating conditions. Fig. 2 illustrated the effect of the pyrolysis temperature on the distribution of bio-product yields (wt %) using different lengths of the ground MPL in ranges of 1-5, 10-15 and 20-25 mm under

**Table 2. The capital cost of the proposed fixed-bed pyrolyzer**

<b>Components of pyrolyzer</b>	<b>Cost (EGP)</b>
LPG cylinder	494
LPG gas regulator	50
Nitrogen gas cylinder	1600
Nitrogen gas regulator	921
Ceramic sensors	825
cables	100
valves	150
Glass wool	75
Cooling serpentine	100
Hoses	30
Galvanized iron sheets	1500
<b>Total</b>	<b>5845 EGP</b>

**Table 3. The actual price (not subsidized) of the energy unit for different energy sources**

<b>Energy Source</b>	<b>Actual price of energy (non-subsidized), EGP</b>	<b>Calorific value, MJ</b>	<b>Price of energy unit, EGP/MJ</b>
Electricity	0.941 EGP/kWh	1 kWh = 3.6	0.261
Natural Gas	3.5 EGP/m <sup>3</sup>	1 m <sup>3</sup> = 36.6	0.096
Liquid Petroleum Gas (LPG)	95 EGP/Cylinder	*1Cylin. (6.12 kg) = 278.66	0.341
Diesel fuel	6.75 EGP/L	1 L = 36	0.188
Gasoline 80 (Benzene)	6.5 EGP/L	1 L = 32	0.203

\*40% propane and 60% Butane

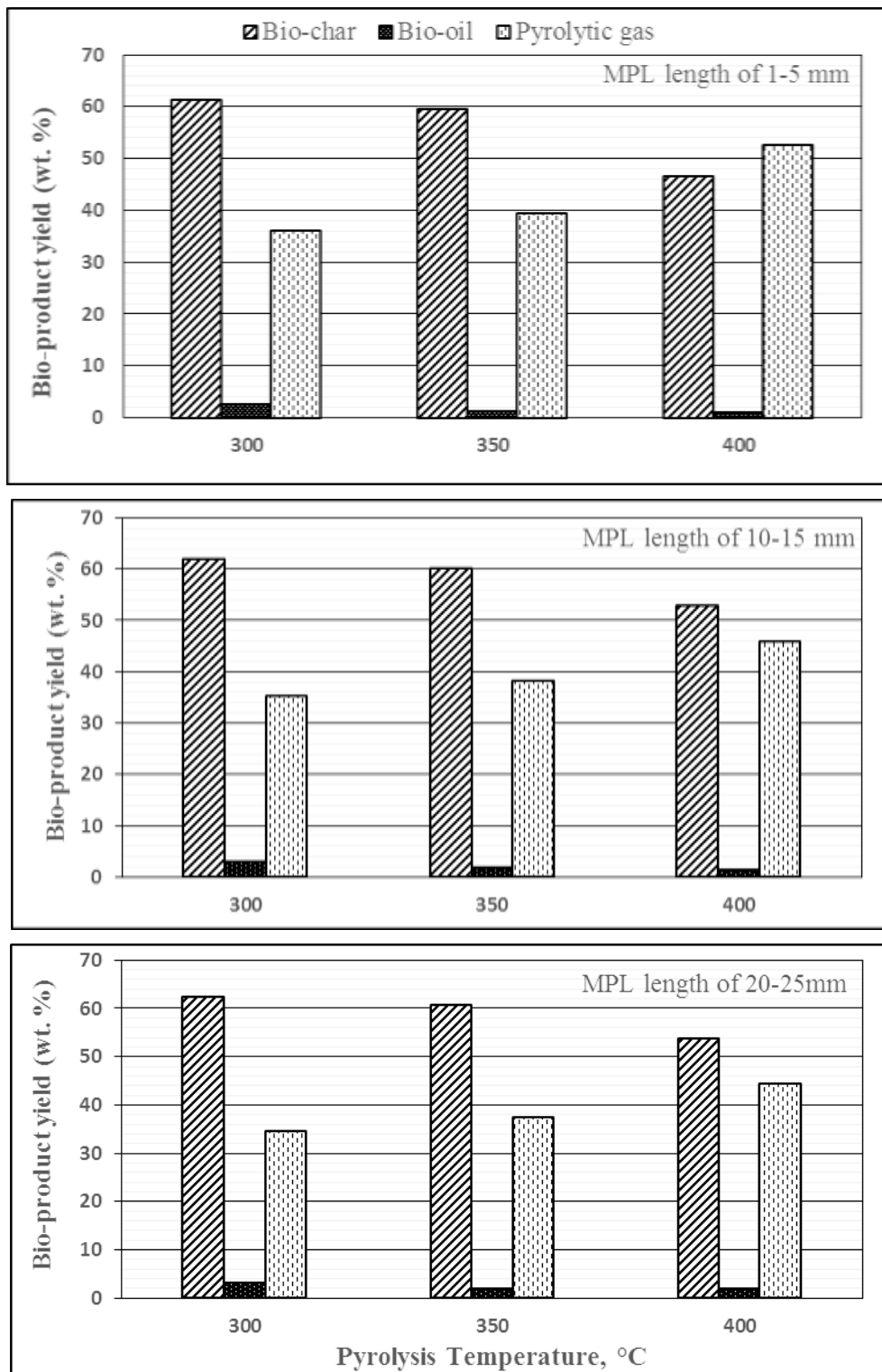


Fig. 2. Effect of pyrolysis temperature and feedstock length on the distribution of the bio-product yields



slow pyrolysis conditions including residence time of 4 min and heating rate of 0.01-1°C/s. The obtained results showed that, the dominant yields were bio-char and pyrolytic gas, besides low yield for bio-oil. This can be explained according to (Basu, 2010) that, the slow removal of volatiles from the pyrolyzer within the final stage of pyrolysis at temperature range of ~300-900°C involves secondary cracking of volatiles into char and non-condensable gases. It is observed that, the increase of pyrolysis temperature and MPL length from 1-5 to 20-25 mm are followed by apparent increase in the pyrolytic gas on the account of bio-char that decreased alongside the bio-oil. So, it is clear that the distribution of bio-product yield is highly influenced by the pyrolysis temperature. The obtained results indicated that the increase of pyrolysis temperature from 300 to 400°C using MPL length of 1-5mm led to the highest increase in the pyrolytic gas by weight from 36.1% to 52.5% and decrease in the bio-char and bio-oil from 61.3% to 46.50% and 2.6% to 1%, respectively. On the other hand, the increase of pyrolysis temperature from 300 to 400°C using longer biomass pieces in ranges 10-15 mm and 20-25 mm led to increase the pyrolytic gas by weight in range from 34.5% to 45.77% and decrease the bio-char and bio-oil in ranges of 62.3-52.9% and 3.2- 1.33%, respectively. Although the MPL has high content of cellulose to produce high bio-oil yield, but the slow removal of condensable vapor due to the long residence time in the pyrolyzer along to the high heat transfer because the shorter pieces of biomass were led to a secondary cracking and hence more yields for the pyrolytic gas and bio-char. Hence, operating the fixed-bed under slow pyrolysis condition using shorter MPL length of 1-5 mm gave an increment in pyrolytic gas yield by about 12.81% and 15.35% over MPL lengths of 10-15 mm and 20-25 mm, respectively at pyrolysis temperature of 400°C. Hence, it was clear that increase pyrolysis temperature from 300-400°C and decrease of the ground MPL length from 20-25 to 1-5 mm was accompanied with an increment in the pyrolytic gas concentration by about 34.28%.

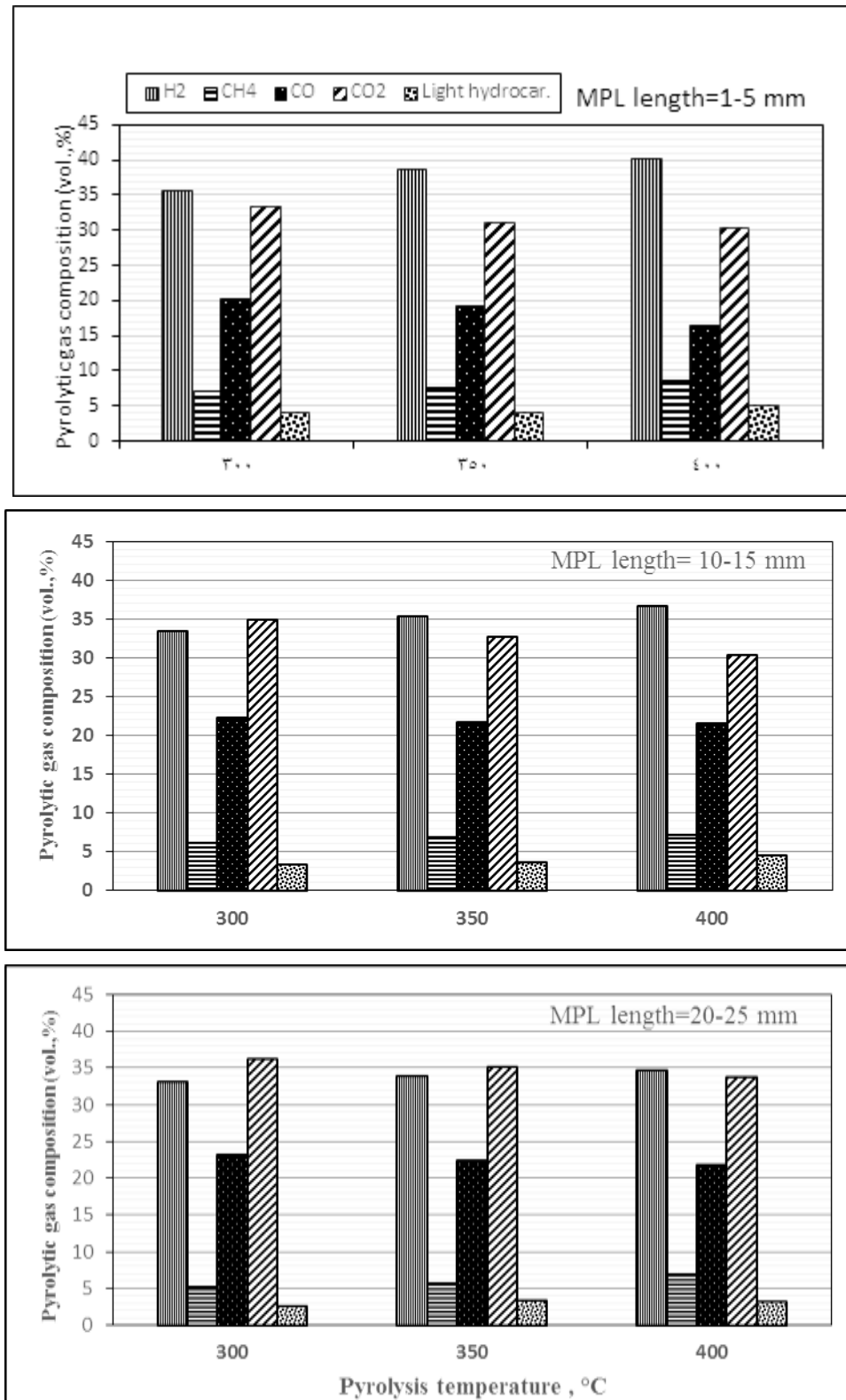
### Effect of the Pyrolysis Temperature and Feedstock Length on of Pyrolytic Gas Composition

The pyrolytic gas was a mixture of gases that mainly consists of H<sub>2</sub>, CO, CH<sub>4</sub>, CO<sub>2</sub> and fractions

of light hydrocarbons. Fig. 3 depicted the effect of pyrolysis temperature on the volumetric percentage of pyrolytic gas components using different lengths of the ground MPL under slow pyrolysis conditions that mentioned earlier. Generally, the obtained results revealed that both of H<sub>2</sub> and CO<sub>2</sub> have the higher concentration in the product gas in ranges of 33.06-40.08 vol.% and 30.12-36.15 vol.%, respectively under pyrolysis temperature range of 300-400°C and MPL lengths range of 1-25 mm. This could be due to the water-gas shift reaction (Domínguez *et al.*, 2008):



From Fig. 3, it can be seen that the increase of pyrolysis temperature is accompanied with clear increase in the concentration of H<sub>2</sub>, CH<sub>4</sub> and light hydrocarbon, while CO and CO<sub>2</sub> are decreased. The results showed that the increase of pyrolysis temperature from 300 to 400°C using the MPL length of 1-5 mm is led up to increase the concentrations of H<sub>2</sub>, CH<sub>4</sub> and other hydrocarbons from 35.57 to 40.08 vol.%, from 7.26 to 8.38 vol.% and from 3.88 to 5.058 vol.%, respectively. However, the concentration of CO and CO<sub>2</sub> were decreased from 20.14 to 16.36 vol.% and from 33.15 to 30.12 vol.%, respectively. Meanwhile, the same trend was observed in case of using the MPL lengths of 10-15 mm and 20-25 mm but either the increase concentrations of H<sub>2</sub>, CH<sub>4</sub> and other hydrocarbons or the decrease of concentration of CO and CO<sub>2</sub> were very slightly. The combination of moderate pyrolysis temperature of 400°C, shorter length of biomass of 1-5 mm and the relatively long residence time may lead to the CH<sub>4</sub> can be released by the reforming and cracking of heavier hydrocarbons in the pyrolysis vapor as secondary reaction (Yu *et al.*, 2016). Additionally, releasing H<sub>2</sub> needed to high energy which can be offered by using small pieces of biomass that offers higher rate of heat transfer comparing to the big ones. It is clear that the pyrolysis temperature and shorter length of biomass have a clear influence on the pyrolytic gas composition under the slow pyrolysis conditions. In the light of above, the highest concentrations of the combustible gases in pyrolytic gas under the slow pyrolysis conditions that represent in H<sub>2</sub> (40.08%), CH<sub>4</sub> (8.38%) and CO (16.36%) are achieved at pyrolysis temperature of 400°C and MPL length of 1-5 mm.



**Fig. 3.** Effect of pyrolysis temperature on the volumetric percentage of pyrolytic gas components using different lengths of the ground MPL under slow pyrolysis conditions

### Effect of the Pyrolysis Temperature and Feedstock Length on a Higher Heating Value of Pyrolytic Gas and Yield

The energy content of the MPL's sample was estimated and expressed in term of the higher heating value ( $HHV_b$ ) to be 21.53 MJ/kg as showed in Table1. The core of this study was to investigate the probable enhancement of the produced pyrolytic gas using the proposed system under slow pyrolysis mode, thereafter the prospective overall goal of the study may be achieved. Thence, this discussion will be focused on one form of bio-product represents in the pyrolytic gas. Actually, the higher heating value of the pyrolytic gas ( $HHV_g$ ) can be affected by the MPL characteristic and operational factors affected by the biomass composition, which was determined by the concentration of combustible gases in the gas generated by the pyrolysis represents in CO, H<sub>2</sub>, CH<sub>4</sub> according to Eq.4. Fig. 4 depicted the effect of pyrolysis temperature and MPL's Length on the  $HHV_g$ . It can be seen that the  $HHV_g$  values of pyrolytic gas are almost increased slightly by increasing the pyrolysis temperature and the decrease in length of the ground MPL under the slow pyrolysis conditions. The obtained results indicated that, the lowest

$HHV_g$  of 9.50 MJ/Nm<sup>3</sup> was recorded at pyrolysis temperature of 300°C and MPL's length of 20-25 mm, while the highest value of 10.88 MJ/Nm<sup>3</sup> was achieved at pyrolysis temperature of 400°C and MPL's length of 1-5 mm. Based on the Chemic analysis of MPL samples showed in Table1, it is clear that the combined amount of hemicellulose with cellulose was higher than the lignin, therefore the incondensable vapor was higher and produced high concentration of H<sub>2</sub>, CO and CO<sub>2</sub>. Besides, the decomposition of heavier hydrocarbon in a secondary reaction due to the relatively long time of retention time in pyrolysis chamber would release more yield of CH<sub>4</sub> and reform more of combustible gases on the account of CO<sub>2</sub>. In the light of above, it was obvious that the pyrolysis temperature of 400°C and short pieces of MPL (1-5 mm) under the slow pyrolysis conditions are led to high concentration of H<sub>2</sub>, CH<sub>4</sub> and CO. This because the pyrolysis of biomass with high hemicellulose and cellulose led to high concentration of combustible gases according to **Paenpong and Pattiya (2016)**, resulted in high  $HHV_g$  of MPL. In light of above, it is obvious that the increase pyrolysis temperature from 300-400°C and decrease of the ground MPL length from 20-25 to 1-5 mm is led to an increment in the  $HHV_g$  by about 12.68%.

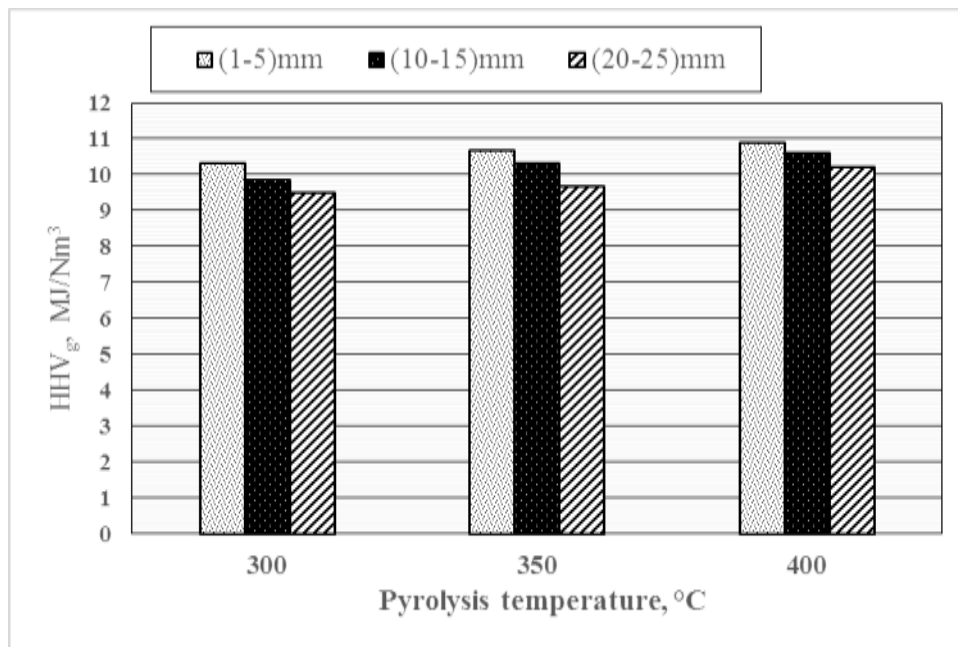


Fig. 4. Effect of pyrolysis temperature on a higher heating value of pyrolytic gas ( $HHV_g$ ) using different lengths of the ground MPL under slow pyrolysis conditions

### Effect of the Pyrolysis Temperature and Feedstock Length on a Pyrolytic Gas Yield (Gy) and Energy Conversion Efficiency ( $\eta_{c-g}$ ) Using Different Lengths

Fig.5 illustrated the effect of the pyrolysis temperature and feedstock length on a pyrolytic gas yield (Gy) using the fixed-bed pyrolyzer under the slow pyrolysis conditions. Based on the chemical composition of MPL used in this study and to the fact of that cellulose and hemicellulose can be decomposed and be released as vapor at lower temperatures compared to lignin (Palamnit *et al.*, 2019), thus more vapor is released from the pyrolyzed MPL, and this results is consistent with Basu (2010) who reported that cellulose and hemicellulose are considered that the main sources of volatiles in ligno-cellulose biomass. As mentioned above, the produced vapor including heavier hydrocarbons may subject to a secondary cracking due to the retention time that mentioned earlier resulted in more incondensable gases would be produced, subsequently the pyrolytic gas yield increased. From Fig.5, it can be seen that the increase of pyrolysis temperature from 300-400°C and decrease of the ground MPL length from 20-25 to 1-5 mm led to an explicit increase in the yield of pyrolytic gas from 0.47 Nm<sup>3</sup>/kg and 1.21 Nm<sup>3</sup>/kg with an increment by about 61.15%.

However, the energy conversion efficiency for pyrolytic gas ( $\eta_{c-g}$ ) can be defined as the ratio of the higher heating value per mass unit of the produced pyrolytic gas (HHV<sub>g</sub>) to the higher heating value of its parent biomass (HHV<sub>b</sub>). This parameter can be used as an indicator for the capability of the proposed pyrolyzer to convert the parent biomass to gaseous bio-fuel represents in pyrolytic gas through producing high concentrations of combustible gases wherein, this indicator depends upon the energy content for both, the biomass and pyrolytic gas. Hence, the high energy conversion efficiency is desirable. Fig.6 depicted the effect of pyrolysis temperature and MPL length on the energy conversion efficiency for pyrolytic gas under the slow pyrolysis condition that used in this study. From the obtained results, it can be seen that the increase pyrolysis temperature from 300-400°C and decrease of the ground MPL length from 20-25 to 1-5 mm is accompanied with increase in the energy conversion efficiency for pyrolytic gas from 20.74% to 61.18% with clear increment by about 66.10%.

### Cost Analysis for the Generated Pyrolytic Gas Process Using the Proposed Pyrolyzer under Slow Pyrolysis Conditions

Fig.7 illustrated the results of cost per energy unit of the generated pyrolytic gas from the ground MPL using the proposed fixed-bed pyrolyzer under the slow pyrolysis conditions, different final temperatures of pyrolysis and different particle lengths ranges. Generally, from the obtained results, it was observed that by increasing the final pyrolysis temperature from 300 to 400°C at using the same particle length the cost per energy unit of pyrolytic gas was increased. It is expected the increase of final pyrolysis temperature means more cost for heating. Furthermore, the high production of bio-char at the lowest pyrolysis temperature of 300°C leads to consider the income of bio-char along with low cost for heating and consequently the cost per energy unit of pyrolytic gas will be the low at this temperature. The obtained results show that the lowest cost of 0.015 EGP/MJ was achieved at pyrolysis temperature of 300°C and particle length of 1-5mm. But in the present study, the optimal cost per energy unit of pyrolytic gas is the cost when the pyrolytic gas had produced with high yield and quality. Hence, the optimal cost per energy unit of pyrolytic gas was 0.085 EGP/MJ (0.005 \$/MJ) that achieved at pyrolysis temperature of 400°C and particle length range of 1-5 mm, as shown in Fig.7.

Additionally, the pyrolytic gas energy criterion cost of the fixed bed pyrolyzer represented in the optimal cost per energy unit of pyrolytic gas that obtained in the present study is compared to the cost per energy unit for different types of energy including the electric energy and fossil fuels taking into consideration the actual prices of energy (not subsidized) in year of 2020, as depicted in Fig.8. It is clear that the natural gas and LPG have the lowest (0.096 EGP/MJ or 0.006 \$/MJ) and the highest (0.341 EGP/MJ or 0.021 \$/MJ) cost per energy unit comparing to the other conventional types of energy. Thence, the cost calculations declared that the optimal cost per energy unit of pyrolytic gas (0.085 EGP/MJ or 0.005 \$/MJ) saved the cost per energy unit by about 11.45% and 75.07% compared to the natural gas and LPG, respectively. It can be concluded that the produced pyrolytic gas from ground MPL under the slow pyrolysis condition used in this study is very potential from the economic aspect.

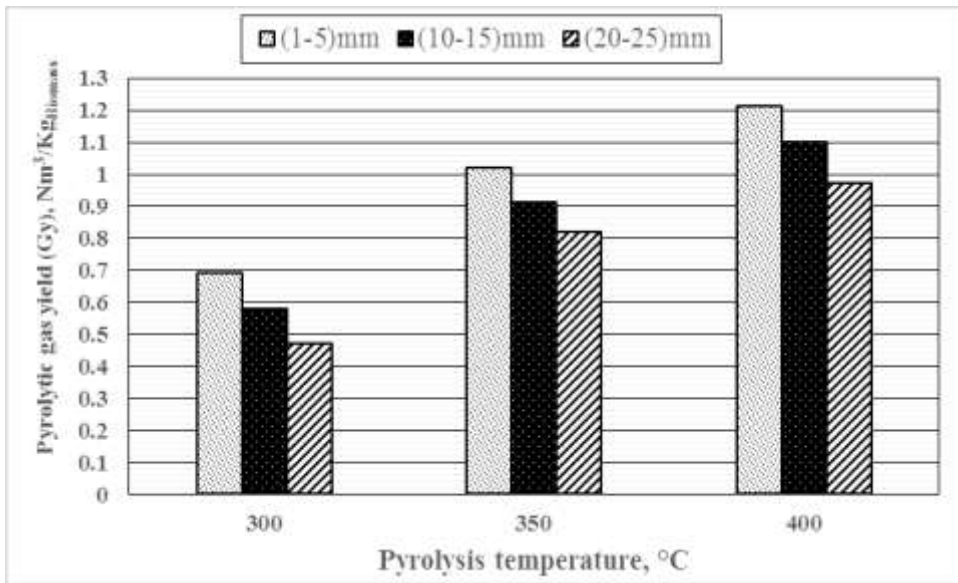


Fig.5. Effect of pyrolysis temperature on gas yield (Gy) using different lengths of the ground MPL under slow pyrolysis conditions

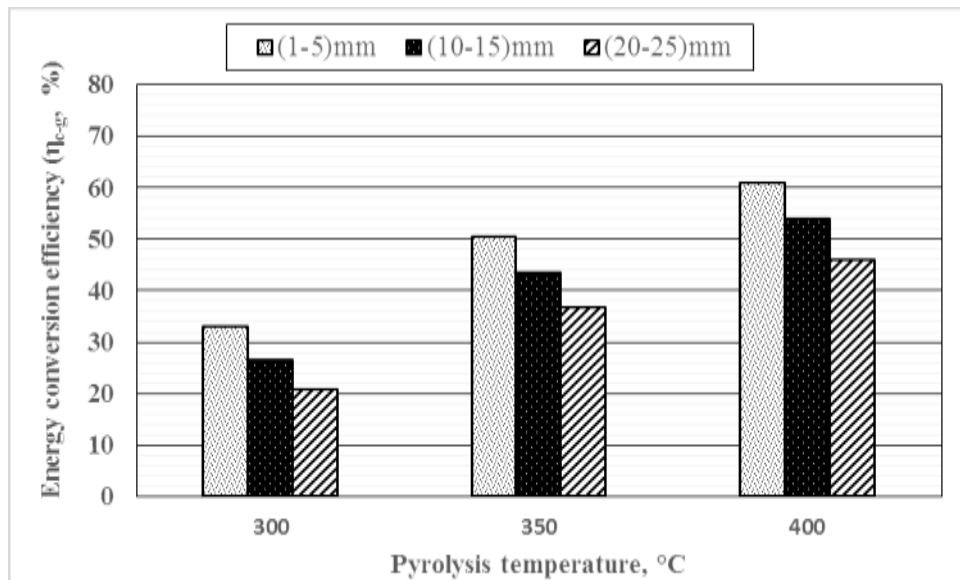


Fig. 6. Effect of pyrolysis temperature on energy conversion efficiency for pyrolytic gas ( $\eta_{c-g}$ ) using different lengths of the ground MPL under slow pyrolysis conditions

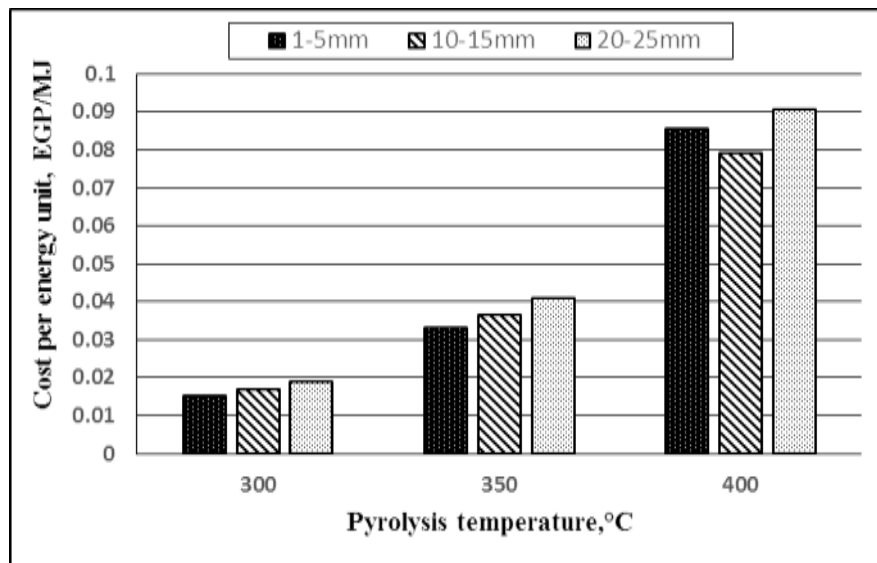


Fig.7. Cost per energy unit of the produced pyrolytic gas using the fixed bed pyrolyzer under different final pyrolysis temperatures and MPL particle lengths

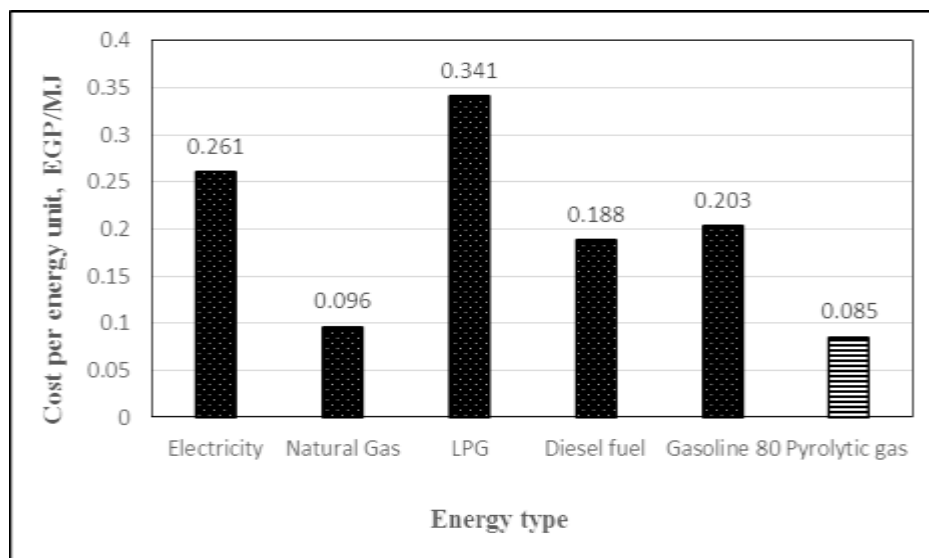


Fig.8. The optimal cost per energy unit of the pyrolytic gas produced from MPL compared to the different types of energy resources

## Conclusion

The slow pyrolysis was suitable for small farms as a simple and economic technique instead of the expensive and complex technique of fast pyrolysis, but it produces primarily the bio-char accompanied with lower production of bio-oil and pyrolytic gas. This work aims to enhance pyrolytic gas yield on the account of bio-char because the probability of using the gas in wide applications in farm. For this purpose, a small-scale fixed-bed pyrolyzer was

fabricated and operated for enhancing the pyrolytic gas from the ground Mango trees Pruning Logs (MPL). The proposed pyrolyzer was tested under different final temperatures of pyrolysis, particle length ranges and slow pyrolysis conditions including heating rate of 0.01-1°C/s and vapor residence time of 4 min. The obtained results indicated that, the operation of proposed pyrolyzer at final pyrolysis temperature of 400°C using MPL's length of 1-5 mm Affords the highest concentrations of the combustible

gases in pyrolytic gas mixture that represent in H<sub>2</sub> (40.08%), CH<sub>4</sub> (8.38%) and CO(16.36%), resulting in higher heating value of 10.88 MJ/Nm<sup>3</sup>. Additionally, the highest concentration of pyrolytic gas, gas yield and energy conversion efficiency were 52.5%, 1.21Nm<sup>3</sup>/kg and 61.18%, respectively are achieved under the same operating conditions. From the economic point of view, optimal cost per energy unit of pyrolytic gas (0.085 EGP/MJ or 0.005 \$/MJ) is lower than cost per energy unit of the natural gas and LPG by about 11.45% and 75.07%, respectively, so the produced gas can be utilized partially to provide the pyrolyzer with required heat for biomass decomposition instead of fossil fuels. Eventually, it is clear that final pyrolysis temperature and the length of biomass pieces are sharply affected production and quality of the pyrolytic gas under the slow pyrolysis process.

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## تحسين إنتاج غاز الإنحلال الحراري الناتج عن الإنحلال الحراري البطيء باستخدام محل حراري ذو المرقد الثابت

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الإنحلال الحراري البطيء للكثلة الحيوية باستخدام المحل الحراري ذو المرقد الثابت هي تقنية بسيطة و منخفضة التكاليف و التي يمكن إستخدامها في المزارع الصغيرة إذا ما قورنت بالتقنية المعقدة و مرتفعة الثمن الخاصة بالإنحلال الحراري السريع. هذه التقنية تستخدم في الأساس لإنتاج الفحم الحيوي إلى جانب إنتاج منخفض من الزيت الحيوي وغاز الإنحلال الحراري وبالتالي فإن هناك حاجة ملحة لتحسين إنتاج غاز الإنحلال الحراري تحت ظروف عملية الإنحلال الحراري البطيء علي حساب الفحم الحيوي بسبب ما يتميز به غاز الإنحلال الحراري من مرونة الإستخدام في التطبيقات المختلفة داخل المزرعة. ومن هنا فإن هذا البحث يهدف إلى تصنيع وتشغيل المحل الحراري ذو المرقد الثابت على نطاق إنتاجي صغير لتحسين إنتاجية غاز الإنحلال الحراري من بقايا التقليم المقطعة لأشجار المانجو تحت ظروف الإنحلال الحراري البطيء (معدل تسخين 0.01 - 1 درجة مئوية/ثانية، زمن لإبقاء الأبخرة داخل المحل 4 دقائق) وبمعزل عن الأوكسجين. تم دراسة إنتاج الغاز تحت درجات حرارة نهائية مختلفة للإنحلال الحراري وهي 300، 350 و 400 درجة مئوية وأطوال مختلفة لبقايا تقليم أشجار المانجو المقطعة وهي 1-5، 10-15، 20-25 مم. أظهرت النتائج المتحصل عليها أن زيادة درجة حرارة الانحلال الحراري النهائية من 300-400 درجة مئوية و تخفيض أطوال بقايا تقليم أشجار المانجو المقطعة من 20-25 إلى 1-5 مم أدت إلي زيادة واضحة في كل من حجم غاز الإنحلال الحراري في ناتج الإنحلال، إنتاج الغاز، القيمة الحرارية للغاز وكفاءة تحويل الطاقة للغاز بنسب 34.28%، 61.15%، و 12.68% و 66.10% على الترتيب، وكذلك تم الحصول على أعلى تركيزات للغازات القابلة للإحتراق وأهمها غاز الهيدروجين وغاز الميثان في خليط غاز الإنحلال الحراري. بالإضافة إلي ذلك فإن التكلفة المثلي لوحة الطاقة لغاز الإنحلال الحراري (0.085 جنيه مصري/ميغا جول) كانت أقل من تكلفة وحدة الطاقة لكل من الغاز الطبيعي وغاز المسال بحوالي 11.54% و 75.07% على الترتيب.

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