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IMPROVE THE PYROLYTIC GAS PRODUCTION BY USING THE CO-PYROLYSIS TECHNIQUE : AN EXPERIMENTAL STUDY

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ABSTRACT

The target of the biomass co-pyrolysis is improvingthe heating value of the produced bio-products of a certain type of feedstock, besides disposal of more than one residue in the same time. Thus, this work aims to operate a local fabricated fixed-bed pyrolyzer to improve the pyrolytic gas yield produced by the ground pieces of three biomass residues namely Mango trees Pruning Logs (MPL), Sugarcane bagasse (SB) and Rice straw (RS) using an affordable slow pyrolysis technique. This work was carried out under slow pyrolysis conditions represented in final pyrolysis temperature of 400 °C, vapor residence time of 4 min, heating rate of 0.01-1 °C/s in full absence of oxygen. The pyrolytic gas production was assessed under different feedstock mixing ratios of (1:2:1), (1:1:2) and (2:1:1) as ratio of (RS: SB: MPL), particle lengths of 1-5, 10-15 and 20-25 mm, with and without sandy bed at the bottom of pyrolysis chamber as a fluidized bed. The obtained results showed that, using the fluidized fixed-bed pyrolyzer under slow co-pyrolysis conditions gave the optimum results where in, the pyrolytic gas concentration, gas yield, higher heating value of pyrolytic gasand energy conversion efficiency were 55%, 1.09 Nm^3/kg, 14.97 MJ/Nm^3 and 85.43%, respectively, and 53.7%, 1.08 Nm^3/kg, 13.75 MJ/Nm^3,77.71% in case of using the pyrolyzer without fluidized bed under the same operating conditions. So, the pyrolyzer with fluidized bed achieves an increment in the higher heating value and energy conversion efficiency by about 8.15% and 9.03%, respectivly over the pyrolyzer without fluidized bed.Furthermore, the cost per energy unit of pyrolytic gas produced by the fluidized bed pyrolyzer is lower than the common two fossil gaseous fuels of natural gas and LPG costs by about 28.57% and 80%, respectively.

***Keywords*:** Co-pyrolysis, Slow pyrolysis conditions, Fluidizedbed, Pyrolyzer performance, pyrolysiscost.

INTRODUCTION

Energy is considered the main drive of the development towards progress, and flourishment on the level of economy, education, health and lifestyle in any country (Tawfik and Abd Allah, 2019). The renewable sources of energy and technologies have the ability to solve the long-standing energy issues facing developed countries (Kumar *et al.,* 2010). Over the past few years, many countries have succeeded to exploit the resources available as biomass feedstock to generate electricity and thermal power. Egypt has multiple sources of biomass that enable it to become one of those (Abd El-Sattar *et al.,* 2019). Generally, Egyptian farms have recently produced annually about 43 Mega ton of the agricultural residues16 Mega ton from these residues has been utilized and the rest would be remained as a type of pollution (Abd El-Sattar *et al.,* 2017). Meanwhile, fruit tree pruning contributes 12.3% of total national residues FAO (2017). Rice straw is one of the most troublesome wastes among biomass feedstock varieties, as it is produced in large quantities seasonally in Egypt; more than 3 million tons per year Zolghadr (2013). Sugarcane bagasse is expected to be processed at 540 million t/y globally, showing the scope for large-scale biofuel processing in sugarcane fields Bezerra and Ragauskas (2016). In most cases, agricultural residues are direct burnt in open field or left to rot down. Biomass is known to be one of the most possible renewable energy sources to contribute to the needs of the energy in modern society Galadima and Muraza (2015). Via a variety of processes, including thermal and biological processes, biomass fuels and residues may be converted to more useful energy sources. In particular, pyrolysis is the process of thermal decomposition that takes place in the complete absence of oxygen and has a tremendous capacity to turn biomass into products of high energy density, like bio-oil, bio-char and pyrolysis gas Kan *et al.,* (2016). Particularly, co-pyrolysis is a mild method of thermal conversion. It is an important mean of directly extracting low-carbon fuels and high-value chemicals from feedstock. However, typical pyrolysis is normally carried out to a certain degree through physical mixing of experimental samples (Yang *et al.,* 2014). The technique of using slow co-pyrolysis is a very important method in order to get rid of more than one residue, during one treatment and to determine the proportions of pyrolysis products by controlling the change of the chemical composition ratios of the biomass during the treatment from its counterpart in the case of mono-pyrolysis. The quantity and quality of the pyrolysis yield is affected by various process parameters (e.g. heating rate, temperature, residence time, pressure) Gomez *et al.* (2016); Zhao *et al.* (2018), reactor type Isahak *et al.* (2012), feedstock type and characteristics (size, structure and shape) Akhtar and Amin (2012). For biomass pyrolysis in general, final pyrolysis temperature of

400 ºC is appropriate to enhance the pyrolytic gas production under the slow pyrolysis condition using the fixed-bed pyrolyzer (Abo Zahra *et al.,* 2021). The biomass pyrolysis has the advantages of producing three forms of bio-fuels represents in bio-char, bio-oil and pyrolytic gas in different percentages comparing, whereas the other thermochemical conversion process that represents in the gasification process gives the syngas as a sole form of bio-fuel. Besides, pyrolysis gases are useful products for fuel and heat generation in motors and power plants, and bio-char, with its wide surface area, can be used to make activated carbon Auta *et al.* (2014). Besides, the bio-product of bio-char produced by the pyrolysis process has another benefit as an organic fertilizer over inorganic fertilizers in that their non-carbonized fraction can interact with soil pollutants, improving soil properties Ahmad *et al.* (2014). In fixed-bed pyrolyzer, using the sand layer at the bottom of pyrolysis chamber to create a fluidized during the co-pyrolysis process may provide the biomass particles with considerable amount of heat due to the low specific heat of the sand. In light of above, this work aims to investigate the potential enhancement of the heating value and yield of the pyrolytic gasby using the fluidized fixed-bed pyrolyzer comparing to the same pyrolyzer with non-fluidized bed under the slow pyrolysis that as a simple and cheap technique. Thepresent work focus to enhance the pyrolytic gas production because it can be used in many applicationsin the farm comparing to the other bio-products (e.g. bio-char, bio-oil). Additionally, co-pyrolysis process using the pyrolyzer with and without fluidized bed was analyzed from the economic point of view and compared to the common fossil fuels used in heating pyrolyzer such as natural gas and LPG.

MATERIALS AND METHODS

Materials:

1. Biomass Feedstock Characteristics:

In this investigation, mango trees Pruning Logs (MPL), Sugarcane Bagasse (SB) and Rice Straw (RS) are naturally dried to the range of 10.33 to 10.93%, afterwards these residues were chopped and ground in small pieces with different length varied from 1 to 25 mm using disc chipper (Tawfik and El-Didamony, 2017) to be used in different mixing ratios through the co-pyrolysis process. The gross and elemental compositions of MPL, SB, and RS pieces were determined using proximate, ultimate, and chemical analysis, as shown in Table (1). The proximate, ultimate and chemical analyses were performed at laboratories of the Faculty of Agriculture, Zagazig University, Egypt. The ground feedstock samples were kept in firmly sealed plastic bags as a standard process prior to the practical experiments (Sakulkit *et al.*, 2020) and also to be used for the proximate, ultimate and chemical analyses.

2. The proposed prototype fixed-bed pyrolyzer:

The proposed prototype fluidized-bed pyrolyzer that presented by Abo Zahra *et al.* (2021) is consisted of a fludizied-bed pyrolysis unit, cooling serpentine, bio-oil collector and N_2 gas cylinder, as depicted in Fig. 1.

-The fluidized-bed pyrolysis unit

The pyrolysis and burner chambers are made in cylindrical shape consisting of galvanized iron sheet provided with three temperature ceramic sensors (K-type) that embedded in the pyrolysis chamber wall. The exterior surface of this unit is wrapped with 4.7 cm of thickness glass wool. The burner chamber is situated underneath the pyrolysis chamber and where it is used to provide heat energy to the feedstock bed. Five cm in thickness of a sandy layer is placed on the bed of the pyrolysis chamber as inert material. The pyrolysis unit is carried on three iron trestles with total height of 40 cm above the ground.

-Cooling serpentine

This part is made of copper and has an internal diameter of 1.387 cm, an external diameterof 1.587 cm, a length of 160 cm, and separated by 10 cm interval distances.

-Bio-oil collector:

The bio-oil collector is made of iron with a hump at the bottomwith 10 cm in diameter and 13 cm in depth.This part allocated nearby to the outlet port of cooling serpentine to collect the condensable gases, which is known as bio-oil.

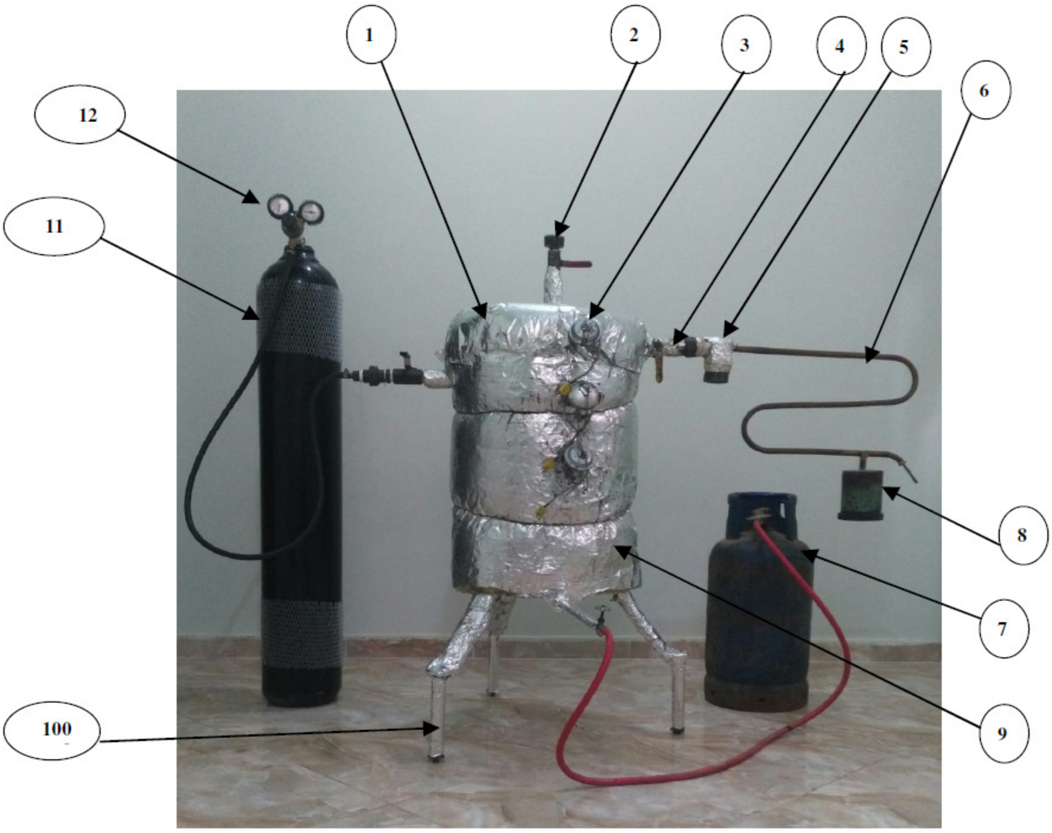
- N_2 gas cylinder

To allow co-pyrolysis process takes place in the absence of air and to prevent the occurrence of oxidation, a nitrogen gas(N_2) was injected into the pyrolysis chamber with pressure of 5 bar for a period of three minutes to sweep the air from the chamber’s enclosure. This gas is packed in a cylinder with a pressure of 150 bar and a capacity of 6 m^3 with a purity of 99.99%.

Table 1 : The elemental and chemical analyses of the ground MPL, SB and RS.

Biomass feedstock	MPL	SB	RS
Proximate analysis, Wt%(db*)			
Moisture content	10.93	10.33	10.49
Total solids (TS)	89.07	89.67	89.51
Ash	6.77	3.9	14.18
Volatile matter	69.74	78.89	65.4
Fixed carbon**	23.49	17.21	20.42
Ultimate analysis, Wt%(db*)			
C	54.24	48.06	43.59
N	0.14	0.7	0.84
H	5.80	6.00	5.8
O**	39.72	44.92	49.67
S	0.10	0.32	0.10
Chemical analysis, Wt%(db*)			
Lignin	26.90	21.60	13.10
cellulose	39.00	40.75	37.80
Hemicellulose	27.50	33.20	22.60
HHV_b (MJ/Kg)***	21.53	19.14	16.61

**(wt% db)=weight percentage on dry basis* ***calculated by difference* ****HHVb=higher heating value of biomass*



No.	Name of part
1	Pyrolysis chamber
2	N_2 vent
3	Ceramic sensors
4	Vapors outlet tube
5	Fly ash cyclone
6	Cooling serpentine
7	LPG cylinder
8	Bio-oil collector
9	Burner chamber
10	Iron trestles
11	N_2gas cylinder
12	N_2gas regulator

Fig. 1 : Photo of the experimental setup of the proposed fixed-bed pyrolyzer used for the co-pyrolysis of the ground MPL, SB and RS

Methods:

Experimental procedure

The experimental procedure in this study were carried out according to Abo Zahra *et al.* (2021). Whilst, the measuring instruments that used in this work are:

- Digital thermometer:

A multi-channels digital data logging thermometer (Model TM-747DU-4-channel, Taiwan) was used to measure the temperature distribution through the vertical axis of the pyrolysis chamber by using calibrated K-type ceramic thermocouple sensors.

-Hot-Wire Air Velocity meter:

Hot-Wire Air Velocity meter (TENMARS, TM-4002, Taiwan) was used to determine the flow rate of pyrolytic gas that received from the outlet port of the cooling serpentine (flame port). The pyrolytic gas flame from the co-pyrolysis process is depicted shown in Fig. 2.

Fig. 2 : The pyrolytic gas flame from the pyrolysis process.

-Gas Chromatography (GC):

A rubber bladder was used to collect the produced pyrolytic gas samples prior to the elemental analysis by the GC, as shown in Fig. 3a. The samples analysis of the pyrolytic gas was carried out using gas chromatography (Scion 456, UK), as seen in Fig.3b. The GC equipped with two channels both (TCD and FID) detectors to detect H_2, CH_4, CO, CO_2 and light hydrocarbons at the Egyptian Petroleum Research Institute (EPRI), Cairo, Egypt.

Fig. 3: The pyrolytic gas analysis: a)The rubber bladderb) the gas chromatography.

Experimental conditions

According to the previous works indicated that the most decomposition of biomass occurred at temperatures ranging from 200 to 400 ºC (Sakulkit *et al.,* 2020). In particular 400 ºC which considered the optimum final pyrolysis temperature that can give the highest quality and quantity of pyrolytic gas under slow pyrolysis conditions including heating rate of 0.01-1 ºC/s and vapor residence time in pyrolysis chamber of 4 minutes(Abozahra *et al.,* 2021). Hence, the performance of the proposed fixed-bed pyrolyzer was evaluated using the co-pyrolysis of different biomass feedstock under slow pyrolysis conditions with and without fluidized bed. The operating conditions used in this work can be described as follows:

1. Co-pyrolysis process for three different types of biomass feedstock including MPL, SB and RS using different mixing ratio of (1:2:1), (1:1:2) and (2:1:1) as ratio of (RS: SB: MPL).
2. Three particle lengths (PL) of the ground pieces of the mixed residues in ranges 1-5, 10-15 and 20-25 mm.
3. Using the co-pyrolysis technique with and without a fluidized bed that represents in 5 cm in thickness of sandy layer as inert material placed on the bed of the pyrolysis chamber that may improve the rate of the heat transfer in attempt to accelerate the decomposition rate.

Measurements and determinations

-Moisture content

The moisture content of the biomass feedstock of MPL, SB and RS was determined by using an oven furnace at a temperature of 105°C for 24 hours according to the following relation (Basu, 2010):

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

Where:

M.C= the moisture content of sample (%),

M_w and M_d= the sample mass before and after drying (g), respectively.

- Heating value of the mixed residues in the co-pyrolysis process

The higher heating value of biomass (HHV_b) is used as an indicator of the energy contained in the biomass feedstock. The HHV_b of the different mixing ratios of MPL, SB and RS was estimated by the following formula (Channiwala and Parikh, 2002):

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

where:

C, H, S, O, N, and A=the total percentages of carbon, hydrogen, sulfur, oxygen, nitrogen and ash, respectively for each mixing ratio on a dry basis.

- The heating value of the pyrolytic gas produced by the co-pyrolysis process

The higher heating value of the pyrolytic gas (HHV_g) produced by the co-pyrolysis process can calculated (Suwannakuta, 2002) as:

$$HHV_g = 13.1(CO\% /100) + 13.2(H_2\%/100) + 41.2(CH_4\%/100), \text{ MJ/ Nm}^3 \quad .... (3)$$

Where:

CO%, H_2%, and CH_4%= are the volumetric percentages of carbon monoxide, hydrogen, and methane, respectively in the pyrolytic gas using the co-pyrolysis process.

- Pyrolytic gas yield

the gas yield (G_y) is calculated as the ratio of pyrolytic gas to the quantity of the parent dry biomass according to following relation **(Gai and Dong, 2012)**:

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

-Energy conversion efficiency for pyrolytic gas (η_{c-g})

The energy conversion efficiency of pyrolytic gas (η_{c-g}) using the proposed pyrolyzer with and without the fluidized bed can be determined using the following equation:

$$\eta_{c-g} = \left(\frac{HHV_g \times G_y}{HHV_b}\right) \times 100\% \qquad (5)$$

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

The life cycle cost analysis was used to evaluate the proposed pyrolyzer either with or without fluidized bed assuming the expected life of 10 years. The capital costs of the fixed-bed pyrolyzer are presented in Table (2) according to 2020 prices. Subsequently, cost per unit of produced pyrolytic gas energy by the co- pyrolysis process can be calculated using the following equation 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 (USD).

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:

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

Where:

P_O= Present operating cost ($).

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

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

Where:

P_{Net} = Net present cost ($).

P_{FI} = Capital cost ($).

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

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

-Annualized cost

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

Where:

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

- Average Cost per unit of generated pyrolytic gas energy

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

Where:

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

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

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

Table 2 : The initial cost of the proposed pyrolyzer

Components of pyrolyzer	**Cost ($)**
LPG cylinder	29.06
LPG gas regulator	2.94
Nitrogen gas cylinder	94.12
Nitrogen gas regulator	54.18
Ceramic sensors	48.53
cables	5.88
valves	8.82
Glass wool	4.41
Cooling serpentine	5.88
Hoses	1.76
Galvanized iron sheets	88.24
Total	**343.82 $**

Table 3 : The actual price (not subsidized) of the energy unit for the conventional gaseous fuels

Energy Source	**Actual price of energy (non-subsidized), $**	**Calorific value, MJ**	**Price of energy unit, $/MJ**
Natural Gas	0.205 $/m^3	1 m3 = 36.60	0.0056
Liquid Petroleum Gas (LPG)	5.588 $/Cylinder	*1Cylin. (6.12 kg) = 278.66	0.02

*40% propane and 60% Butane.

RESULTS AND DISCUSSION

1- Effect of the feedstock mixing ratio and fluidized bed on the bio-product yields of co-pyrolysis at different particle length (PL):

Depending on the operating conditions, the co-pyrolysis produces primarily three forms of bio-products represented in bio-char, bio-oil, and pyrolytic gas with different distribution percentages depending up on the operating conditions and the chemical properties of each type of feedstock within the mixture. Figs. (4 and 5) show that the effect of the feedstock mixing ratio of RS, SB and MPL and on distribution of the bio-product yields of co-pyrolysis process with and without fluidized bed. According to Basu (2010), increasing the lignin content of biomass feedstock leads to an increase in the production of bio-char, while the high content of the cellulose leads to increase the bio-oil yield and finally, hemicellulose plays a large role in the production of the pyrolytic gas. Thus, the chemical composition of the biomass is considered one of the most effective factors that influence the distribution of the bio-product yields of the co-pyrolysis process. From the obtained results, it was observed that with any particle length of residues mixture and the optimum pyrolysis final temperature of 400ºCeither using the pyrolyzer with or without fluidized bed, the feedstock mixing ratio of (1:1:2) led to produce high bio-char yield followed by the ratio of (1:2:1) and (2:1:1). This may be due to the high amount of lignin in the biomass mixture (1:1:2) according to (Soltes and Elder, 1981). On the other hand, using the mixing ratio of (1:2:1) leads to the highest pyrolytic gas yield due to the increased hemicellulose content, followed by the ratio (1:1:2), then (2:1:1), where this result agreed with Reed (2002). The data showed that, the increasing in particle length from 1-5 mm to 20-25 mm using the same feedstock mixing ratio led to increase the bio-char yield, while the pyrolytic gas and bio-oil yields were decreased. It is obvious that the shorter particles in the mixed biomass has the advantages of the large surface area per unit volume that can lead to increase the devolatilization rate of the biomass component with help of the slow pyrolysis condition represented in the long residence time of vapor inside the reaction zone resulted in more carbon will go through secondary cracking stage and non-condensable gases will be generated and this means increasing the pyrolytic gas yield on the account of bio-char and bio-oil. Besides, using pyrolyzer with fluidizedbed (sandy layer as catalyst medium) at the bottom of the pyrolysis chamber with advantage of the direct contact with ground particles of biomass mixture of (RS:SB: MPL) for co-pyrolysis process led to the supply the biomass particles with considerable amount of heat due to the low specific heat of the sand. Hence, the decomposition of biomass in the reaction zone inside the pyrolysis chamber will be relatively accelerated. Generally, it was found the mixing ration of (1:2:1) gave the highest yield for pyrolytic gas by weight on the account of bio-char. As shown in Fig. 4, the decrease of the particle length from 20-25 mm to 1-5 mm using this mixing ratio and the fluidized-bed led to increase the pyrolytic gas and bio-oil from 48.20% to 55% and from 1.80% to 3%, respectively, whilst the bio-char decreased from 50% to 42%. In case of using the pyrolyzer without fluidized bed, that the pyrolytic gas and bio-oil from 46.10% to 51.70% and from 1 % to 2.70%, respectively, whilst the bio-char decreased from 52.90% to 43.60%, as depicted in Fig.5.Hence, it is obvious that the decrease of particle length from 25-20 mm to 1-5 mm using mixing ratio of (1:2:1) under pyrolysis temperature of 400 ºC and slow pyrolysis conditions gave a clear increment in pyrolytic gas yield by weight by 12.36% and 10.83% with and without fluidized bed, respectively.

2- Effect of the feedstock mixing ratio and fluidized bedon a volumetric percentage of pyrolytic gas composition at different particle length(PL):

The pyrolytic gas is one of the most vital products of the biomass pyrolysis process due to its flexible uses as source of thermal or mechanical energy which can be utilized in wide range of applications. It is a mixture of gases composed primarily of hydrogen (H_2), carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4) and traces of other hydrocarbons. Figs. (6,7) depicted the effect of the biomass feedstock mixing ratio on a volumetric percentage of pyrolytic gas composition at different particle lengths using the co-pyrolysis technique with and without fluidized bed. Generally, using the feedstock mixing ratio of (1:2:1) under the slow co-pyrolysis process and pyrolysis final temperature of 400 ºC either with or without fluidized bed gave the highest concentration of the combustible gases including H_2, CH_4, CO as well as other hydrocarbons gases, and the lowest concentration of CO_2 comparing to the other mixing ratios of (2:1:1) and (1:1:2) using the same length of the mixed feedstock. It is obvious that, the increase of SB as double of both MPL and RS in the mixing ratio would increase volumetric percentage of the combustible gases and decrease the concentration of CO_2. Meanwhile, the particle length of the biomass feedstock has a great influence on the pyrolytic gas composition produced by the co-pyrolysis under slow pyrolysis conditions. Regardless of the feedstock mixing ratio, the obtained results indicated that the decrease in the particle length from 20-25 mm to 1-5 mm led to a rapid thermal decomposition rate causes an improvement in carbon conversion rate, and hence the concentration of the combustible gases in the pyrolytic gas (i.e. H_2, CH_4, CO) and other hydrocarbons will increase. The presence of a sand layer as a catalyst medium for the feedstock during the pyrolysis process caused the continuity of the carbon conversion due to the low thermal capacity of the sand. This can lead to an improvement of pyrolytic gas composition according to the reforming and cracking of heavy hydrocarbons in pyrolysis vapors due to the long residence time of the slow pyrolysis. Fig.6 show that the decrease of particle length from 20-25 to 1-5 mm using the co-pyrolysis technique with a fluidized bed and the optimum mixing ratio of (1:2:1) was followed by an increase in the volumetric of percentage of H_2, CH_4 and other hydrocarbons from 38 to 45.11 vol.%, 10.29 to 15.34 vol.% and 4.39 to 7.98 vol.%, respectively. In meantime, the volumetric of percentage of CO and CO_2 in the produced pyrolytic gas was decreased from 27.91 to 20.58 vol.% and from 19.40% to 10.97 vol.%, respectively. Under the same operating conditions, the experimental data of co-pyrolysis process without fluidized bed and the optimum mixing ratio of (1:2:1) indicated that the volumetric of percentage of H_2, CH_4 and other hydrocarbons in the pyrolytic gas increases from 36.88 to 42.39 vol. %, 9.77 to 13.97 vol. % and 4.08 to 6.07 vol.%, respectively as shown in Fig.7. Meanwhile,the volumetric of percentage of CO and CO_2 in the produced pyrolytic gas was decreased from 26.05 to 18.28 vol.% and from 23.20to 19.28 vol.%, respectively. Ultimately, it can be summarized that using the pyrolyzer with fluidized bed under the slow co-pyrolysis conditions using particle length of 1-5 mm and mixing ratio of the blended biomass residues of (1:2:1) gave the highest volumetric percentage of H_2(45.11 vol.%) and CH_4 (15.34 vol.%) in the produced pyrolytic gas accompanied with percentages of 20.58, 10.97 and 8 vol.% for CO, CO_2 and other light hydrocarbons, respectively.

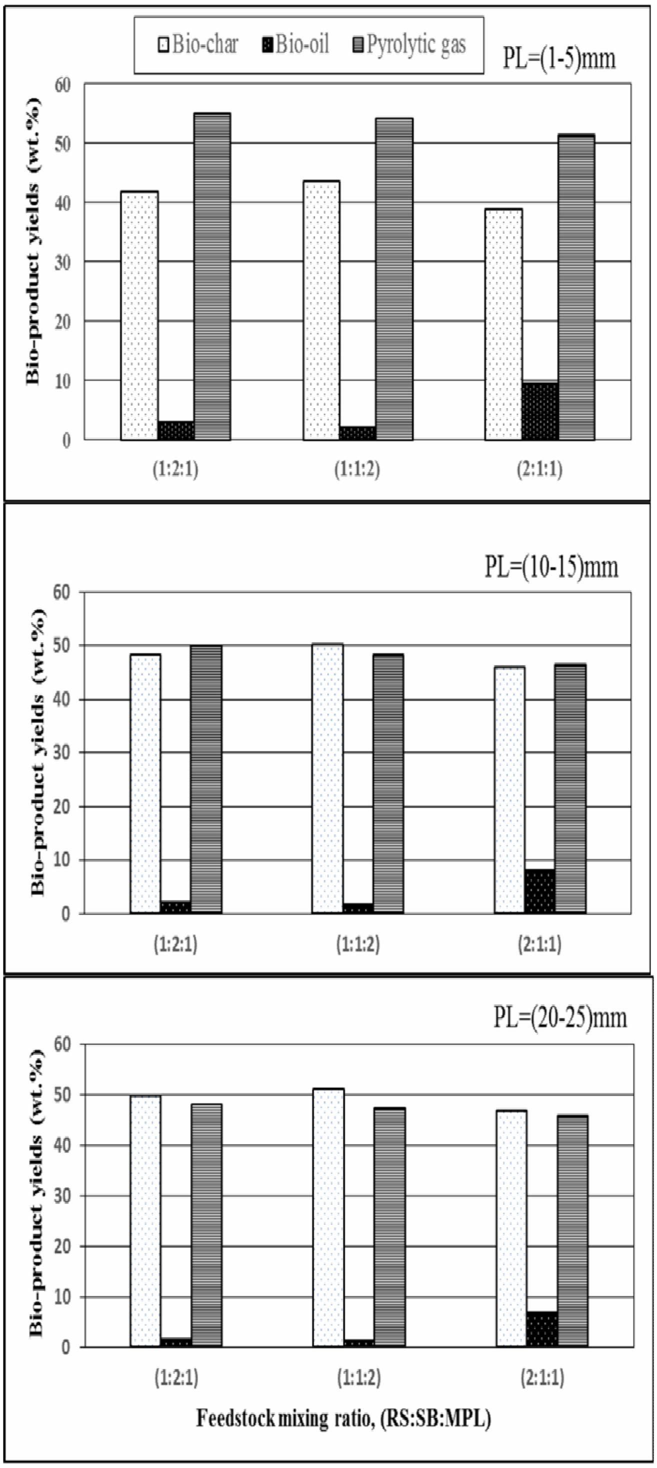


Fig. 4 : Effect of the feedstock mixing ratio on the bio-product yields at different particle lengthswith fluidized bed under slow co-pytolysis process and pyrolysis temeprature of 400 ºC.

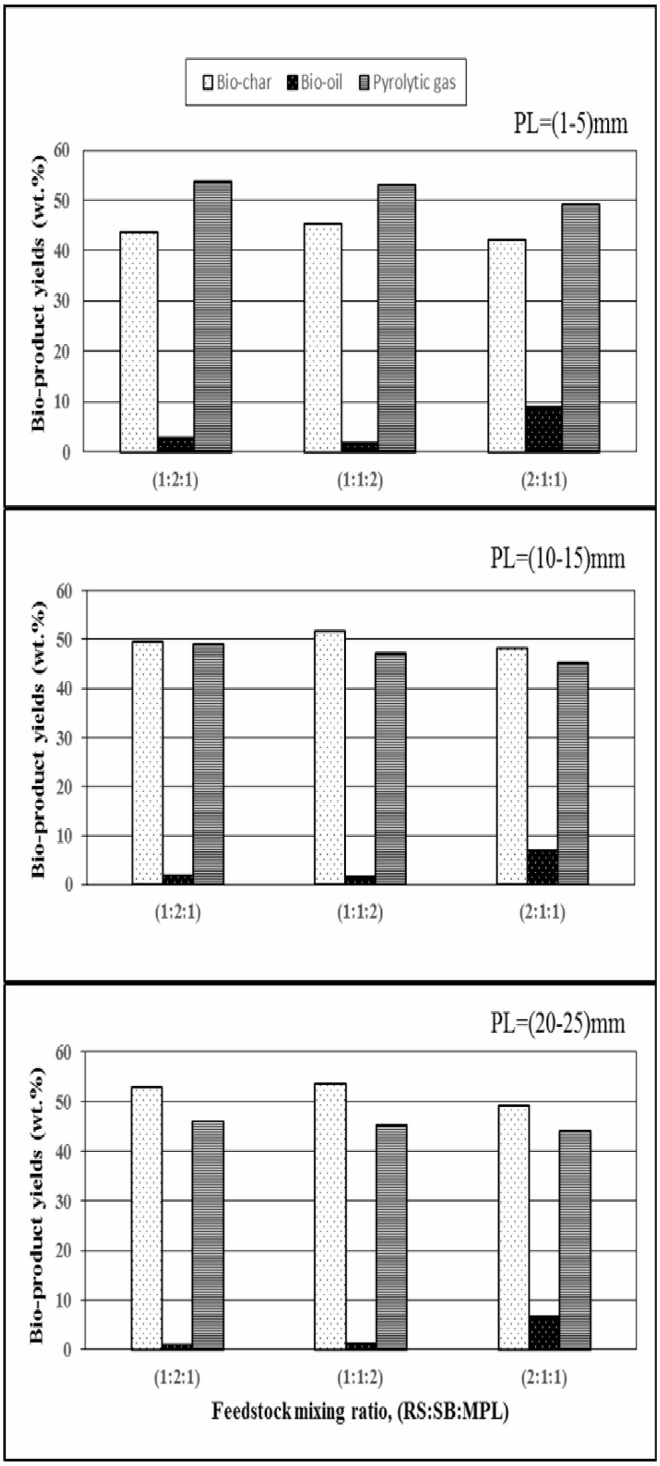


Fig. 5 : Effect of the feedstock mixing ratio on the bio-product yields at different particle lengthswith non-fluidized bed under slow co-pytolysis process and pyrolysis temeprature of 400ºC

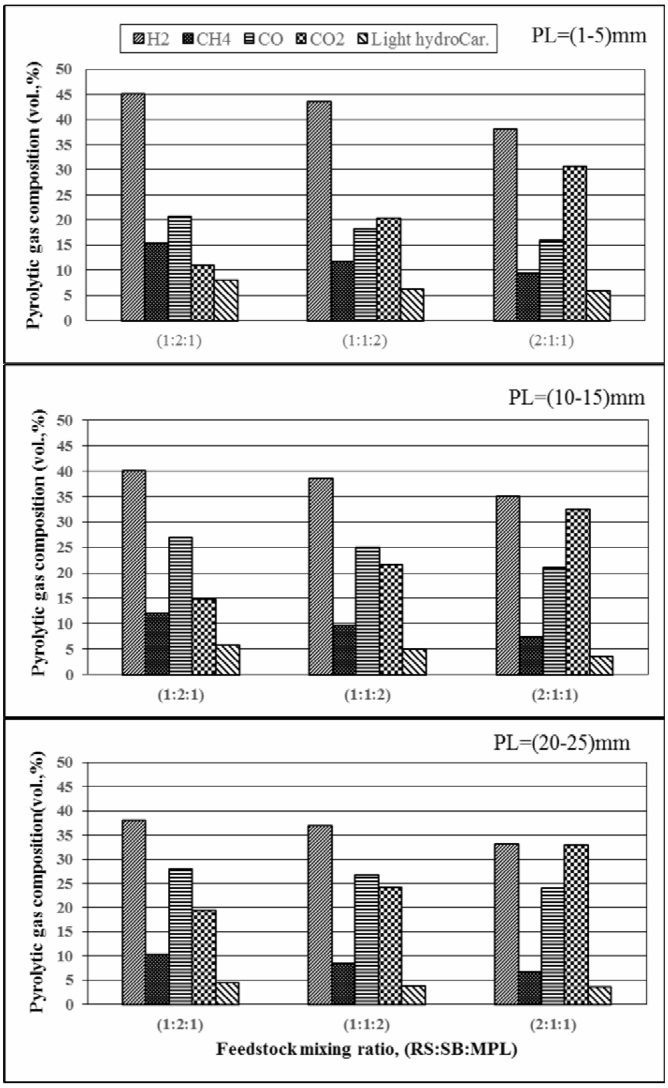


Fig. 6 : Effect of the feedstock mixing ratio on the volumetric percentage of pyrolytic gas composition at different particle lengthswith fluidized bed under slow co-pytolysis process and pyrolysis temeprature of 400ºC

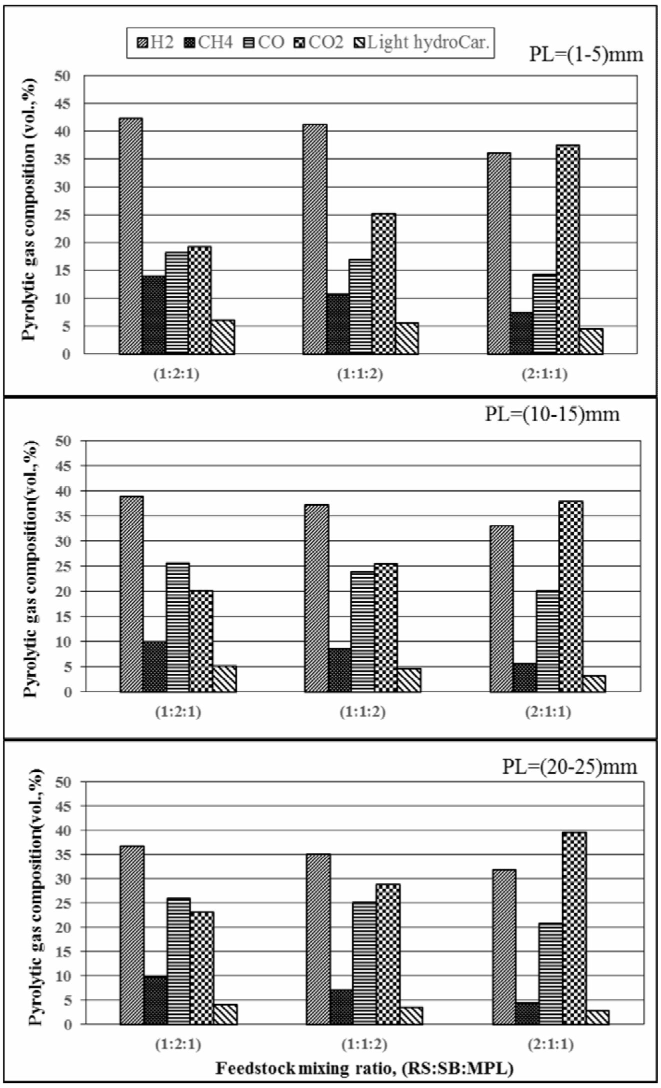


Fig. 7 : Effect of the feedstock mixing ratio on the volumetric percentage of pyrolytic gas composition at different particle lengths with non-fluidized bed under slow co-pytolysis process and pyrolysis temeprature of 400ºC.

3. Effect of the feedstock mixing ratio and fluidized bedon a higher heating value of pyrolytic gas (HHV$_g$) using different particle length (PL):

In this study, the higher heating value (HHV) of RS, SB and MPLs samples was estimated to be 16.61, 19.14 and 21.53MJ/kg $_{\text{biomass}}$, respectively, as illustrated in Table (1). Additionally, the higher heating value for feedstock mixing ratio for the co-pyrolysis experiments is estimated by the higher heating value existing in each feedstock that contributes in the mixture of the blended biomass. On the other hand, the higher heating value of pyrolytic gas is calculated according to the Eq. (3).

Fig. 8 illustrate that the effect of the feedstock mixing ratio of the blended residues on higher heating of pyrolytic gas (HHVg) using different particle lengths of the biomass feedstock either using the pyrolyzer with or without fluidized bed. Generally, the decrease of particle length from 20-25 mm to 1-5 mm using the same feedstock mixing ratio would maximize the HHVg. According to the chemical analysis presented in Table1, it is obvious that the combined amount of cellulose and hemicellulose is higher than the lignin, which may increase the non-condensable vapors produced by the co-pyrolysis process along with the decomposition of heavy hydrocarbons through a secondary cracking step due to the long residence time in pyrolysis chamber, and consequently more concentrations of combustible gases (i.e. H_2 and CH_4, CO) would be generated on the account of CO_2. As mentioned earlier, it was found that the mixing ratio of (1:2:1) gave the highest values of H_2, CH_4 using any particle length of the blended feedstock either with or without fluidized bed, resulted in high value of HHV$_g$. This is can be attributed to the pyrolysis of the high content of hemicellulose and cellulose will contribute to a high yield of combustible gases which agreed with Paenpong and Pattiya (2016). Figs 8 show that the lowest values of HHV$_g$ of 10.21 and 8.82 MJ/ Nm^3 were recorded by using the pyrolyzer with and without fluidized bed, respectively using the feedstock mixing ratio of (2:1:1) and biomass particle length of 20-25 mm under the slow pyrolysis conditions (vapors residence time of 4 minutes and heating rate of 0.01-1 °C/s) and final pyrolysis temperature of 400ºC. On the other side, the highest values of HHV$_g$ were 14.97 and 13.74 MJ/ Nm^3

were achieved by using the pyrolyzer with and without fluidized bed using the feedstock mixing ratio of 1:2:1 and particle length of 1-5 mm under the same operating conditions. From Fig.8a, it can be seen that, the decrease of the particle length from 25-20 to 1-5 mm with fluidized bed under the optimum mixing ratio of 1:2:1, gave an increase in HHV_g by 13.76%.

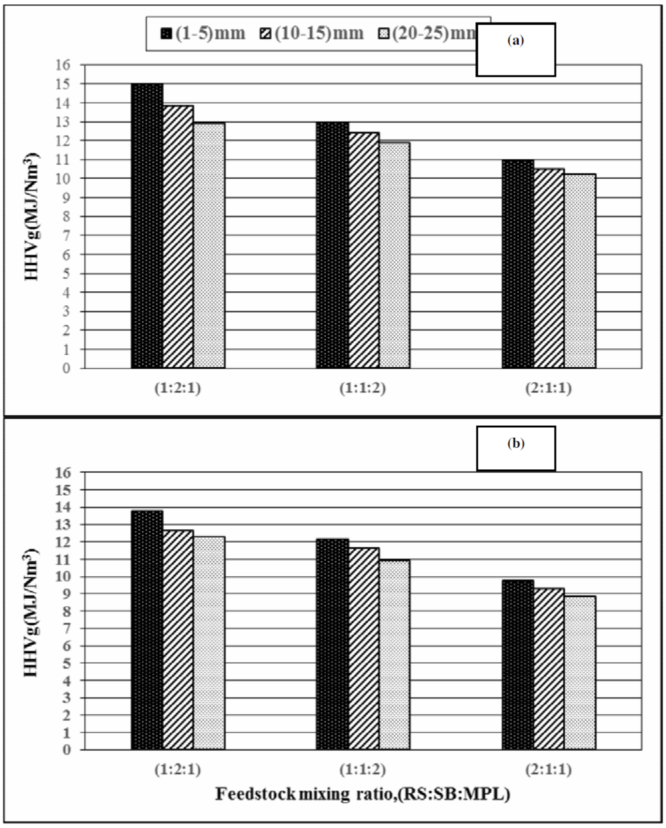


Fig. 8 : Effect of the feedstock mixing ratio on a higher heating value of the HHV_g using different particle lengths under slow co-pytolysis process and pyrolysis temeprature of 400ºC: a) with fluidized bed; b) without fluidized bed.

4-Effect of the feedstock mixing ratio and catalyst medium on a pyrolytic gas yield (G_y) and energy conversion efficiency using different particle lengths (PL):

The pyrolytic gas yield is dependent on the volumetric flow rate of pyrolytic gas and quantity of the dried parent biomass that fed into the pyrolysis chamber. Fig.9(a,b) shows that the influence of feedstock mixing ratio of the blended residues on the pyrolytic gas yield using different particle lengths under the slow co-pyrolysis conditions and final pyrolysis temperature of 400 ºC. In general, it can be observed that, the decrease in the particle length from 20-25 mm to 1-5 mm, was followed by an increase in pyrolytic gas yield from 0.69 to 0.92 Nm^3/kg, 0.89 to 1.06 MJ/ Nm^3 and 0.93 to 1.09 Nm^3/kg for mixing ratios of (2:1:1), (1:1:2) and (1:2:1), respectively using the fluidized. However, decrease in the particle length from 20-25 mm to 1-5 mm, was followed by an increase in pyrolytic gas yield from 0.60 to 0.85 Nm^3/kg, 0.84 to 1.01 MJ/ Nm^3 and 0.9 to 1.08 Nm^3/kg for mixing ratios of (2:1:1), (1:1:2) and (1:2:1), respectively using the non-fluidized bed. As a conclusion, using feedstock mixing ratio of (1:2:1) in form of blended biomass residues gave highest gas yield of 1.09 Nm^3/kg using particle length of 1-5 mm, as depicted in Fig. 9a.

On the other hand, Fig. 10(a,b) illustrate the effect of feedstock mixing ratio (RS: SB: MPL) on the energy conversion efficiency (η_{c-g}) of the pyrolytic gas produced by the fluidized and non-fluidized co-pyrolysis processes using different biomass particle lengths. It can be seen that the decrease of particle length from 20-25 to 1-5 mm using any feedstock mixing ratio would be accompanied with a remarkable increase in the energy conversion efficiency of pyrolytic gas. The highest value of energy conversion efficiency for the pyrolytic gas was obtained at particle length of 1-5mm and feedstock mixing ratio (1:2:1). This can be referred to the increase of pyrolytic gas yield (G_y) and HHV_g of pyrolytic gas either by using the fluidized or non-fluidized co-pyrolysis processes. From Fig.10(a), it was noticed that the decrease of particle length from 20-25 mm to 1-5 mm would be accompanied with an increase in the energy conversion efficiency for pyrolytic gas from 38.15to 54.68 %, 53.58 to 69.69 % and 62.85 % to 85.42% for feedstock mixing ratio of (2:1:1), (1:1:2) and (1:2:1), respectively using the pyrolyzer with fluidized bed. Whereas, the decrease of particle length from 20-25 to 1-5 mm followed by an increase in the energy conversion efficiency for pyrolytic gas from 28.65 to 44.81 %, 46.49to 62.15% and 57.97to 77.70% for feedstock mixing ratios of (2:1:1), (1:1:2) and (1:2:1), respectively using the non-fluidized bed co-pyrolysis process, as shown in Fig.10(b). As seen in Fig.10(a), it is clear that the highest energy conversion efficiency for pyrolytic gas of 85.42% can be obtained by using the fluidized-bed co-pyrolysis process with the short particle length of 1-5 mm, feedstock mixing ratio of (1:2:1) under slow pyrolysis conditions (vapors residence time of 4 minutes and heating rate of 0.01-1 °C/s) and final pyrolysis temperature of 400ºC with a considerable increment by 9.03% over the non-fluidized bed co-pyrolysis process.

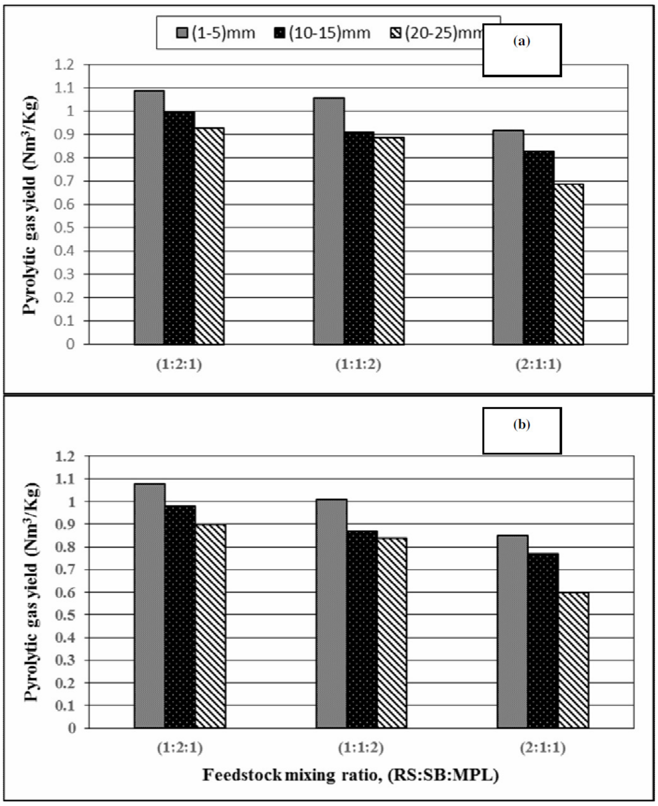


Fig. 9 : Effect of the feedstock mixing ratio on a pyrolytic gas yield using different particle lengths under slow co-pytolysis process and pyrolysis temeprature of 400ºC: a)with fluidized bed; b) without fluidized bed.

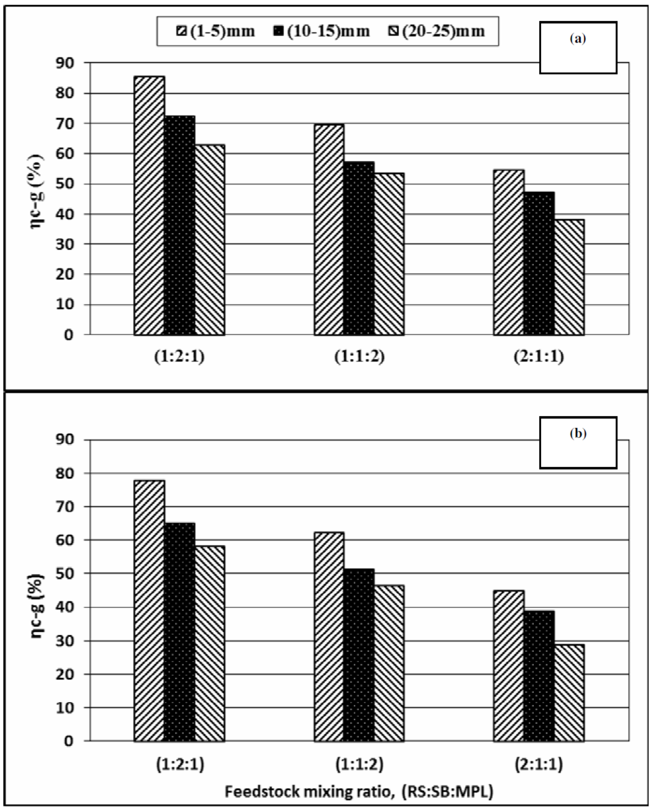


Fig. 10 : Effect of the feedstock mixing ratio on energy conversion efficiency for pyrolytic gas using different particle lengths under slow co-pytolysis process and pyrolysis temeprature of 400ºC: a)with fluidized bed ; b) without fluidized bed.

5- Cost analysis for the generated pyrolytic gas by the fluidized and non-fluidized bed co-pyrolysis process using the proposed pyrolyzer:

Fig.11 (a,b) illustrates the results of the pyrolytic gas cost from the fluidized and non-fluidized bed co-pyrolysis processes. As a general trend, it can be observed that the decrease of the biomass particle length from 20-25 to 1-5 mm with any feedstock mixing ratio, the cost per energy unit of pyrolytic gas produced either from the fluidized and non-fluidized bed co-pyrolysis was increased. This because the decrease of biomass particle length will reduce the cost for heating the pyrolysis chamber due to the quick heat transfer into the particle. Furthermore, the high production of pyrolytic gas using the short particle length 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 decreased. The obtained results showed that the lowest cost of per energy unit of pyrolytic gas produced by the fluidized and non-fluidized bed co-pyrolysis process were0.004 $/MJ and 0.0038 $/MJ, respectively by using feedstock mixing ratio of (1:2:1) and particle length of 1-5mm under slow pyrolysis conditions (vapors residence time of 4 minutes and heating rate of 0.01-1 °C/s) and final pyrolysis temperature of 400ºC. Practically, the optimal cost per energy unit of pyrolytic gas is the cost when the pyrolytic gas had produced with high yield and quality. Accordingly, as per the LCC analysis, the optimal cost per energy unit of pyrolytic gas was obtained to be 0.004 $/MJ under the conditions mentioned above. Accordingly, the optimum cost per energy unit of pyrolytic gas compared to the cost per energy unit for two gaseous forms of fossil fuels energy that commonly used in heating the pyrolysis chamber including natural gas and LPG taking into consideration the actual energy prices (not subsidized) in year of 2020, as depicted in Fig.12. It can be seen that the natural gas has the lower cost per energy unit of 0.0056 $/MJ comparing to cost of LPG 0.02 $/MJ. The cost calculations declared that the optimal cost per energy unit of pyrolytic gas of 0.004 $/MJ saved the cost per energy unit by about 28.57% and 80 % compared to the natural gas and LPG, respectively. Lastly, it can be suggested that the pyrolytic gas produced by co-pyrolysis with fluidized bed under the slow pyrolysis conditions and pyrolysis temperature of 400 ºC is very potential from the economic point of view.

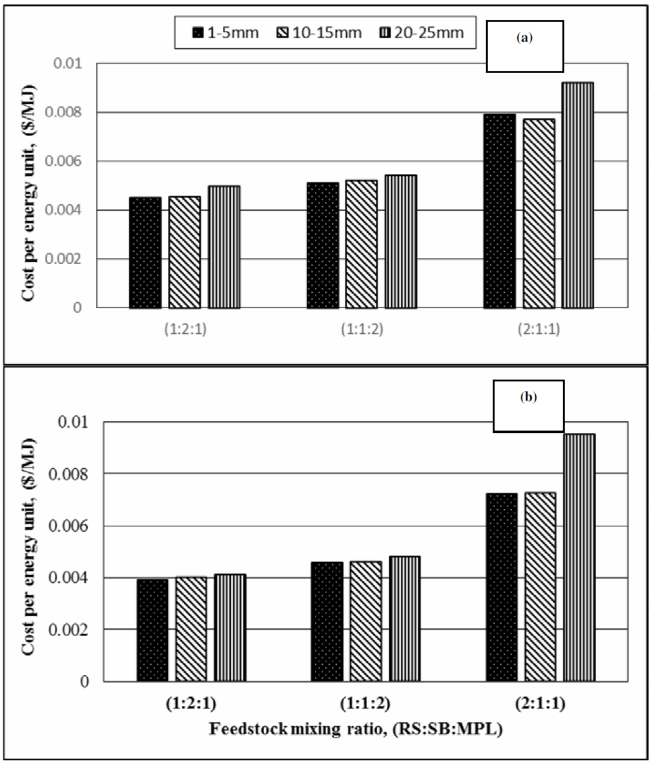


Fig. 11 : Cost per energy unit of the produced pyrolytic gas using different feedstock mixing ratio particle lengths under slow co-pytolysis process and pyrolysis temeprature of 400ºC: a)with fluidized bed; b) without fluidized bed.

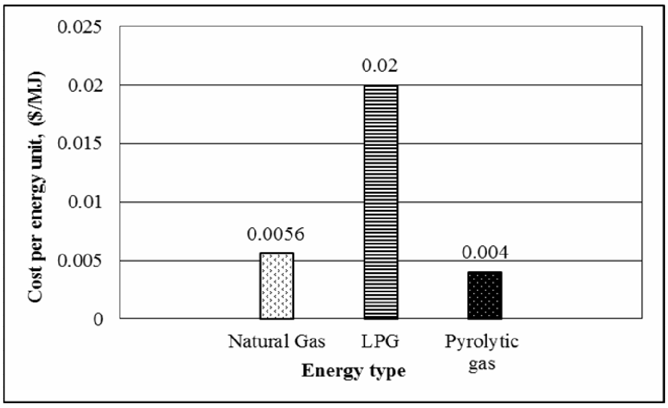


Fig. 12 : The optimal cost per energy unit of the pyrolytic gas produced from co-pyrolysis with fluidized bed compared to two types of fossil gaseous fuels.

CONCLUSIONS

Co-pyrolysis of biomass feed stock is considered as a potential thermochemical conversion method to converts the lignocellulosic materials to useful energy. This is methods used primarily to enhance the heating value of the produced bio-products (e.g. bio-char, bio-oil, pyrolytic gas), meanwhile it is useful to rid of more than one residue at the same time to avoid contamination. Among these bio-products, the pyrolytic gas has an advantage of the possibility to be used as a source of either the heat or/ and mechanical energy in the farm. But, the slow pyrolysis using fixed-bed pyrolyzer type is initially produce high amount of bio-char. Accordingly, this study aims to operate and evaluate the performance of a local made fixed-bed pyrolyzer using slow co-pyrolysis technique with and without fluidized bed to improve the pyrolytic gas production produced from three residues of mango trees pruning logs (MPL), sugarcane bagasse (SB) and rice straw (RS).The practical experiments were carried out under different feedstock mixing ratios of (1:2:1), (1:1:2) and (2:1:1) as ratio of (RS: SB: MPL), particle lengths of 1-5, 10-15 and 20-25 mm, with and without sandy bed at the bottom of pyrolysis chamber as inert medium to be fluidized bed under the slow pyrolysis conditions including final pyrolysis temperature of 400 °C, vapor residence time of 4 min, heating rate of 0.01-1 °C/s.

The obtained results showed that the slow co-pyrolysis technique with the fluidized fixed-bed pyrolyzer using feedstock mixing ratio of (1:2:1) particle length of 1-5mm, gave the followings:

i) The highest combustible gas concentrations of pyrolytic gas represented in H_2 (45.11%), CH_4 (15.34%) and CO (20.58%) which led to obtain the highest values of higher heating value of 14.97 MJ/Nm^3.

ii) The highest concentration of pyrolytic gas, gas yield and energy conversion efficiency of 55%, 1.09 Nm^3/kg and 85.43%, respectively were obtained.

iii) There is a considerable increment was achieved using the fluidized bed pyrolyzer in the higher heating value and energy conversion efficiency by about 8.15% and 9.03%, respectivly over the non-fluidized bed pyrolyzer.

From the economic point of view, the optimum cost per energy unit of pyrolytic gas was to be 0.004 $/MJ, and this is lower than the cost per energy unit for both common gaseous fossil fuels of natural gas and LPG by 28.57 % and 80 %, respectively. Thence, it is clear that the slow co-pyrolysis technique with using the fluidized fixed-bed pyrolyzer is promised either from the performance or economic aspects.

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